An Integrated Strategy for the Planetary Sciences: 1995-2010

SPACE STUDIES BOARD
NATIONAL RESEARCH COUNCIL

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Committee on Planetary and Lunar Exploration
Space Studies Board
Commission on Physical Sciences, Mathematics, and Applications
National Research Council

Washington, D.C. 1994

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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COMMITTEE ON PLANETARY AND LUNAR EXPLORATION

SPACE STUDIES BOARD

COMMISSION ON PHYSICAL SCIENCES, MATHEMATICS, AND APPLICATIONS

Preface

The Committee on Planetary and Lunar Exploration (COMPLEX) advises the Space Studies Board (SSB) on the entire range of planetary science studies; these include both ground-based activities and space-based efforts. The disciplinary scope of its advice includes the geosciences, atmospheres, exobiology, particles and fields, planetary astronomy, and the search for planets around other stars.

COMPLEX's advisory base is made up of a series of reports published over the last 15 years. These documents (see bibliography) establish the scientific goals and objectives in each of the following areas: inner planets, outer planets, primitive solar system bodies, detection and study of other planetary systems, and origins and evolution of life (a responsibility inherited from the SSB's former Committee on Planetary Biology and Chemical Evolution). To date, no COMPLEX strategy has set scientific priorities across the entire field of planetary science. However, because of the increasing competition for limited resources, it is now desirable to undertake this prioritization.

As a result, the SSB charged COMPLEX with carrying out a study to establish a unified set of priorities for the scientific exploration of the planets. In particular, the study was to address the following points:

- Summarize current understanding of the planets and the solar system;
- Pose the most significant scientific questions that remain; and
- Establish the priorities for scientific exploration of the planets for the period from 1995 to 2010.

Early in the preparations for this study COMPLEX decided that it would divide the planetary sciences into broad discipline areas such as solid bodies and interiors, atmospheres, magnetospheres, rings, primitive bodies, and origins. Committee members were assigned to one of these groups on the basis of their individual expertise and knowledge. COMPLEX's membership was also expanded to ensure adequate representation for each discipline area.

The study began with a workshop in Irvine, California, in July 1992. Invited presenters briefed the committee on the latest developments in each of the discipline areas. Following the presentations, COMPLEX members and guests adjourned to discussion groups to produce documents summarizing the status of knowledge in each of the relevant subject areas. These drafts became the foundation on which subsequent phases of the study were built.

Work on the report continued with visits to major centers for research in the planetary sciences. At each site, COMPLEX was briefed on future mission possibilities, while additional presentations were loosely organized around a common theme. The sites visited included NASA-Goddard Space Flight Center, theme: space-based observatories (September 1992); NASA-Jet Propulsion Laboratory, theme: microrobotic technology (January 1993); and University of Arizona, theme: ground-based observatories (April 1993). At each of these locations, COMPLEX gave a public presentation on the nature of its study and invited input from the local community. In some cases, these presentations were followed by extended group discussions with local scientists.

Outreach activities also included a mass mailing (conducted with the assistance of the Lunar and Planetary Institute) to members of the planetary science community soliciting opinions on priorities. A short article about COMPLEX's study was published in *Eos, Transactions, American Geophysical Union*. Additional public presentations about the committee's activities were made at various universities and research centers as well as at a number of major national and international scientific conferences, including those of the American Astronomical Society's Division for Planetary Sciences (October 1992, Munich, Germany) and the American Geophysical Union (December 1992, San Francisco, California), and the Lunar and Planetary Science Conference (March 1993, Houston, Texas). Representatives from the European Space Science Committee participated in several of COMPLEX's meetings. In addition, COMPLEX cooperated with and coordinated its activities in areas of mutual interest with the SSB's Committee on Solar and Space Physics and the Board on Atmospheric Sciences and Climate's Committee on Solar-Terrestrial Research, currently engaged in drafting a joint research strategy for solar and space physics.

COMPLEX's final list of priorities was drafted at a workshop held in Woods Hole, Massachusetts, in July 1994. The priorities were set following an extensive series of ballots (both public and private) using a variety of procedures designed to test the validity of the results. Consistent results were obtained whether the committee members voted as individuals or collectively by discipline group. In other words, top-rated priorities received both broad individual support and broad discipline support.

COMPLEX appreciates the time and thoughtful attention provided by the many individuals, too numerous to list, who contributed to this study; in particular, the comments and criticisms of reviewers of early drafts of this report are gratefully acknowledged. Of course, the findings, conclusions, and judgments of this report are solely the responsibility of the committee.

Joseph A. Burns, *Chair*
Committee on Planetary and
Lunar Exploration

Contents

Executive Summary

The reasons given for supporting the U.S. program in solar system exploration differ from group to group. The public believes that the program should follow the essential tradition of exploring Earth to learn what is there and how it can benefit the human race. According to policy makers, the nation funds the planetary and lunar program for the purposes of exploration and adventure; promotion of science education; stimulation of technology; and enhancement of national pride, prestige, and security. For scientists, the primary purpose of exploring the Moon and planets is to advance knowledge. By choosing to stress one or another of these aspects, substantially different strategies for exploring the solar system might be developed.

In 1992, the National Research Council's Space Studies Board charged its Committee on Planetary and Lunar Exploration (COMPLEX) to:

- Summarize current understanding of the planets and the solar system;
- Pose the most significant scientific questions that remain; and
- Establish the priorities for scientific exploration of the planets for the period from 1995 to 2010.

For this report, COMPLEX has based its recommendations on the expected science yield for a level of effort at which research needs to be done to sustain a vigorous field. Any activity less than this effort would, over the time frame of the strategy, raise questions as to whether the sponsoring agency is fostering genuine progress in the planetary sciences.

The broad scientific goals of solar system exploration include:

- Understanding how physical and chemical processes determine the major characteristics of the planets, and thereby help us to understand the operation of Earth;
- Learning about how planetary systems originate and evolve;
- Determining how life developed in the solar system, particularly on Earth, and in what ways life modifies planetary environments; and
- Discovering how relatively simple, basic laws of physics and chemistry can lead to the diverse phenomena observed in complex systems.

This report is written under the assumption that Galileo and Cassini, both missions of the highest priority, will complete their major objectives as understood in mid-1994. The report also assumes that the various ground-based facilities (e.g., NASA's Infrared Telescope Facility, Keck I and II [when completed], and the Kuiper Airborne Observatory) will continue operating and that the Hubble Space Telescope will continue to produce the superb data exemplified by the results obtained after the servicing mission. It supposes that NASA will, at a minimum, fund research and analysis (R&A) activities at current levels. COMPLEX also believes that many of the major facilities suggested by the National Research Council's Astronomy and Astrophysics Survey (Bahcall) Committee, namely the Space Infrared Telescope Facility, the Stratospheric Observatory for Infrared Astronomy, an infrared-optimized 8-meter telescope (Gemini, North), a Southern Hemisphere 8-meter telescope (Gemini, South), and the Millimeter Array, could make unique planetary observations.

This report provides a framework for setting previous COMPLEX recommendations in their relative scientific priority. Unless stated otherwise, COMPLEX endorses its past recommendations for exploration of the Moon and planets.

The committee has written this document with several different audiences in mind. Decision makers in Congress, NASA, and other organizations should focus their attention on this Executive Summary and Chapters 1 and 6 (supplemented by material from Chapters 2 and 5). Research scientists and graduate students may be most interested by the science summaries in Chapters 3 and 4, as well as the final priority list given in Chapter 6.

SCIENCE QUESTIONS AND OBJECTIVES

For the purpose of describing current knowledge of the solar system, this report is organized by combining the broad scientific goals listed above into two themes:

- How planetary systems and life originate, and
- How planets work.

For each topic under these broad headings, the report summarizes current scientific knowledge, lists the key remaining questions, and suggests the primary objectives for future research. For brevity, this Executive Summary does not describe today's understanding of these various themes, even though this understanding forms most of the main text of this report. To provide an idea of some contemporary research issues for planetary science, a list of important scientific questions is given immediately below. From a synthesis of these research objectives, COMPLEX concluded that investigations of a few particular objects, by a multiplicity of techniques, are likely to be especially fruitful. A synopsis of the arguments for emphasizing these objects closes this Executive Summary.

Primary Objectives for Understanding Origins

Questions of origins have intrigued mankind since the beginning of time but have only recently begun to be addressed scientifically. In the last decade major advances in solving the puzzles of origins have been made, both observationally and theoretically. This is an emerging research topic that should continue to progress rapidly in the next 15 years as improved detectors and more capable computers provide new insights as to how the solar system and extrasolar planetary systems formed.

Protoplanetary disks, out of which all planetary systems are believed to arise, are now being routinely identified and characterized. Yet, to date, we have scant evidence for extrasolar planets. Nonetheless, to significantly improve our understanding of how the solar system originated, we must obtain a statistically significant sample of data on the frequency of planetary systems around other stars and on their basic properties.

Life is thought to have arisen from unexceptional organic material contained in the matter from which the solar system grew as a consequence of everyday photochemical and biochemical processes. Comets, asteroids, meteorites, and interplanetary dust grains—so-called primitive materials—offer important constraints to possible early histories of the planetary system because they are relatively unaltered.

The key scientific objectives for the study of protoplanetary disks, planetary systems, primitive materials, and life are the following (in no particular order).

Protoplanetary Disks

- Develop (through theoretical modeling) a detailed understanding of the aggregation of stellar and planetary systems, starting at the formation phase of dense molecular cloud cores.
- Observe nearby star-forming regions to obtain data that can guide and constrain our understanding of protostellar formation.
- Define the conditions and processes active during the evolution of the solar nebula through laboratory analysis of meteorites and interplanetary dust particles and observations of primitive solar system objects, such as comets and asteroids.

Planetary Systems

- Construct an internally consistent, quantitative theory of the formation of our entire planetary system that contains sufficient detail to permit comparison with as much observational evidence as possible, including the meteoritic record.
- Detect and determine the orbital properties of planetary systems circling enough nearby stars to yield a statistically significant estimate of the frequency of planetary systems.
- Ascertain, as soon as is technically feasible, the atmospheric temperatures and compositions of these extrasolar planets.

Primitive Bodies

- Describe the nature and provenance of carbonaceous materials in cometary nuclei, especially as they pertain to the origin of terrestrial life.
- Identify the sources of the extraterrestrial materials that are received on Earth.
- Delineate how asteroids and comets are related and how they differ.
- Determine the elemental, molecular, isotopic, and mineralogic compositions for a variety of samples of primitive bodies.
- Characterize the internal structure, geophysical attributes, and surface geology of a few comets and asteroids.
- Understand the range of activity of comets, including the causes of its onset and its evolution.
- Ascertain the early thermal evolution of primitive bodies, which led to the geochemical differentiation of these bodies.

Life

- Define the inventory of organic compounds in the cores of molecular clouds, and improve our understanding of the prebiotic organic chemistry that took place in the solar nebula.
- Improve knowledge of the processes that led to the emergence of life on Earth, and determine the extent to which prebiotic and/or protobiological evolution has progressed on other solar system objects, specifically Mars and Titan.

Primary Objectives for Understanding Planets

Now that spacecraft reconnaissance of the solar system is drawing to a close, it is no longer sufficient to simply inventory the properties of the solar system's contents. Instead we must also seek to comprehend how planets work. In order to make sense of current information about Earth's siblings, we have divided our knowledge of these bodies into scientific disciplines that are familiar to those who study Earth. Thus, COMPLEX divides planetary bodies into four interrelated components: the surfaces and interiors of solid bodies, planetary atmospheres, rings, and magnetospheres. Nevertheless COMPLEX emphasizes that the nature of an individual planet can be fully appreciated only when the links between these components are clearly understood.

Key objectives for each of these scientific disciplines are the following (in no particular order).

Surfaces and Interiors of Solid Bodies

- Understand the internal structure and dynamics of at least one solid body, other than Earth or the Moon, that is actively convecting.
- Determine the characteristics of the magnetic fields of Mercury and the outer planets to provide insight into the generation of planetary magnetic fields.
- Specify the nature and sources of stress that are responsible for the global tectonics of Mars, Venus, and several icy satellites of the outer planets.
- Advance significantly our understanding of crust-mantle structure, geochemistry of surface units, morphological and stratigraphic relationships, and absolute ages for all solid planets.
- Elucidate the chemical and physical processes (impact cratering, surface weathering, and so on) that affect planetary surfaces.
- Characterize the surface chemistry of the outer solar system satellites, and determine the volatile inventories and interaction of the surface and atmosphere on Triton and Pluto.
- Establish the chronology of at least one other major body in the solar system.

Planetary Atmospheres

- Ascertain the key chemical balances and processes that maintain the current compositions of the atmospheres.
- Specify the processes that control dynamics on the outer planets, on Mars, and on Venus.
- Understand Mars's inventory of volatiles and its evolution and how these relate to historical climate changes.
- Determine reactive-gas isotopic ratios, rare-gas abundances, and isotopic abundances for all the planets with substantial atmospheres, to help understand atmospheric origin, history, and maintenance.

Rings

- Measure the radial, azimuthal, and vertical structure of all the ring systems at sufficient spatial resolution to clarify whether the observed variability is spatial or temporal in nature.

• Determine the composition and size distribution of the ring particles at a few places in several different systems.

• Develop kinematic and dynamic models of ring processes and evolution that are consistent with the best ground- and space-based observations. Insofar as possible, connect these processes to ones that were active as the solar system originated.

Magnetospheres

• Determine how, and the degree to which, plasma and electromagnetic environments affect planetary gas (including the atmosphere), dust, and solid surfaces.

• Understand how solar wind and planetary variations drive magnetospheric dynamics, including substorms, for various magnetospheric conditions.

• Determine the roles of microscopic plasma processes in the mass and energy budgets of planetary magnetospheres, and ascertain the energy conversion processes that yield auroral emissions.

• Discover how differing plasma sources and sinks, energy sources, magnetic field configurations, and coupling processes determine the characteristics of both intrinsic and induced planetary magnetospheres.

• Determine what studies of contemporary planetary magnetospheres tell us about processes involved in the formation of the solar system.

• Characterize the plasma environments and the solar wind interactions of Pluto-Charon and Mars.

BASIC SCIENCE AND INFRASTRUCTURE

While major spaceflight programs have always been NASA's primary emphasis, it has also supported an effective research and analysis (R&A) program. Much excellent science has been accomplished by principal investigators peering through Earth-based instruments, poring over spacecraft data, or numerically simulating complicated systems. This "small science" program precedes and supplements the results returned by spacecraft missions and places these results in context; in many cases this work is independent of the spaceflights and should remain so. Small amounts of additional funding in this area can increase substantially the scientific yield of major missions by assuring that all returned data are carefully processed, scrutinized, and archived. The full analysis of data after the end of a flight is essential to harvest the information. Mission operations, the support of the mission once it is under way, must be funded in such a way that flight programs achieve their full potential.

The R&A program is vital for the future of the flight program because it provides the background information necessary to select the appropriate mission designs and because it trains the cadre of workers who will be needed for scheduled missions. Many of the researchers who will direct the analysis of Cassini data in the first two decades of the next century, for example, are now graduate students supported by R&A funds.

The R&A program is in a weakened condition. Investments need to be made to ensure that capable, state-of-the-art equipment is available in laboratories, computer facilities, and observatories; funds should also be expended to develop flight instrumentation. COMPLEX maintains that a vigorous R&A program is a fundamental requirement for overall success in planetary and lunar exploration.

A mix of "mission" sizes will be necessary to address all the objectives for planetary science. These "missions" will range from support of individual researchers, through construction and maintenance of ground-based telescopes and laboratories, to "low-cost" robotic missions with limited measurement goals, and eventually to large, expensive, multidisciplinary programs akin to Galileo and Cassini.

SCIENTIFIC PRIORITIES FOR PLANETARY EXPLORATION: 1995-2010

It is clear from the scientific summaries given in the main body of this report that exploration of the solar system is far from complete. In fact, the gaps in fundamental information are, in some areas, huge, with many basic issues as yet unresolved. For this reason, it could be argued that *any* planetary exploration activity must be useful for scientific understanding since our information base will expand. Nevertheless, COMPLEX believes that science priorities must be set because some studies are more likely than others to produce answers to fundamental questions. The scientific community does not have the resources, the facilities, or the personnel to undertake all worthy proposals. If priorities are to be chosen, planetary scientists should participate in a major way.

In developing an integrated strategy for the exploration of the solar system, COMPLEX noted that some of the most important objectives for the time frame of this study will be addressed by ongoing missions. Prime among these is an intensive, multidisciplinary investigation of the saturnian system. Rather than reiterate support for this activity, COMPLEX decided that it would be more appropriate to devote the bulk of this report to highlighting four additional areas in which significant progress could be made before 2010 using a variety of techniques and assuming a vigorous exploration program. Furthermore, the list of key unanswered questions and objectives for the various scientific disciplines considered in Chapters 3 and 4 shows that studies of a few locales are most likely to address the most important scientific issues. In order to prioritize among the possible scientific areas, COMPLEX decided to emphasize studies that will address the most important science themes—including locales that will simultaneously answer questions across a range of topics or those objectives that are especially ripe for progress today.

Finally, COMPLEX attempted to balance the perceived scientific importance with the likelihood that significant measurements can be achieved with techniques (including reanalysis of archival data, laboratory and theoretical studies, ground- and space-based observing programs, and remote sensing and in situ studies by small, intermediate, and large robotic missions) currently used or likely to be available before 2010. **COMPLEX maintains that the most useful new programs to emphasize in the period from 1995 to 2010 are detailed investigations of comets, Mars, and Jupiter and an intensive search for, and characterization of, extrasolar planets.**

Comets

COMPLEX believes that the study of the composition of a cometary nucleus is the first among equals because such an investigation would contribute so much to understanding how our solar system originated. In order to obtain the most useful information on the comet's original composition, we must examine the elemental, isotopic, and mineralogical makeup of unaltered materials from beneath the comet's crust.

Comets may also give clues as to the biogenic elements and compounds with which the primordial Earth was endowed. Although, in order to fully achieve this objective, a sample return will ultimately be needed, significant measurements can be carried out by rendezvous missions. In addition to in situ composition studies, unique investigations of such novel phenomena as dusty plasmas can be performed near the nucleus. Furthermore, although cometary rendezvous missions and sample return missions have often been rated highly by scientists, comets have yet to receive detailed scrutiny, in spite of recent distant and/or high-speed flybys of Halley and two other comets. The most critical aspects of these objectives may be satisfied by a mission more focused than the Comet Rendezvous Asteroid Flyby (CRAF) had been; significant progress may be made by participating in a meaningful way in international programs.

Mars

The fourth planet from the Sun is of special interest because, more than any other planet, Mars may help unlock the secrets of Earth. In atmospheric science, the uncertainties are global circulation and climate history. A key to the latter may be dating the polar laminae. It is also important to consider the upper atmosphere and its interaction with the solar wind. The internal structure of any planet, other than Earth, is largely unknown and yet plays a major part in understanding surface morphology and origins; for this reason COMPLEX recommends probing Mars's interior. Mars may also give unique perspectives on the origin of life on Earth. The primary objectives of atmospheric sciences and geophysics will require both long-term global surveillance and the deployment of a network of long-lived monitoring stations.

Jupiter

The Sun's largest planet has a powerful, dynamic atmosphere and a remarkably complex magnetosphere. Jupiter's atmosphere—with its equatorial jets, polar convection cells, and stormy vortices—well represents the outer layers of the other gas giants. To study the atmosphere, a fleet of atmospheric probes and a polar orbiter are recommended. The magnetosphere, which is an archetype for all those that are rotationally driven, is loaded with material injected by the bizarre satellite Io. Volcanic Io is interesting in its own right; it also plays an intimate role in powering the planet's intense aurorae and strong radio emissions as well as in driving the planet's magnetosphere. Major questions will remain after the Galileo mission is completed because even the baseline mission, carrying instruments with 1970s technology, will not have surveyed high-latitude regions or the inner magnetosphere very well.

Extrasolar Planets

While the mere detection of planets around other stars will arouse great public interest, such discoveries alone will not be sufficient for further understanding of how the solar system originated. To build good theoretical models of planetary accumulation, information is needed on the mass, orbital elements, and, for considerations of life as well as the ultimate comparative planetology, atmospheric temperatures and compositions. Refined observations of circumstellar disks will also be valuable in constraining origin scenarios.

Other Important Objects

Given the myriad of opportunities for important scientific discoveries in all parts of the solar system, the above list is relatively brief. Although, in COMPLEX's considered opinion, of lesser priority than the four topics described above, strong scientific arguments could be made for devoting additional attention to Pluto, Neptune, or the Moon, or to focused objectives at these and other locations in the solar system. The rationale behind these primary and secondary priorities, and many of the important measurements that need to be made at these objects—as well as at other targets across the solar system—are given in the main text of this report.

1

Why We Study Planets

Great civilizations are remembered for those things that outlive them, be they pyramids and temples, or knowledge and understanding. COMPLEX believes it likely that one of the achievements for which this generation will be best and longest remembered is the exploration of the Moon and planets accomplished during the last third of the twentieth century. To measure the remarkable progress made in understanding the solar system during this period, it is useful to contrast some misconceptions that prevailed 30 years ago with the insights that we now possess. In the early 1960s, the Moon was thought to be a primitive object, and Mars was believed to be possibly the abode of abundant plant life. Today the Moon is known to have experienced, following its birth, nearly a billion years of violent bombardment that left much of its surface pockmarked with impact craters, while Mars is recognized to be a cold, arid planet with a currently hostile environment but a most interesting past. Indeed as a result of spacecraft reconnaissance and ground-based observations, we now have a first-order understanding of the planets and their satellites, from Sun-baked Mercury to frigid Pluto. The motives that drove the United States, the former Soviet Union, and, to a lesser extent, various European nations and Japan to explore the solar system during the last three decades were political as well as scientific. Even though the political motive has virtually disappeared, COMPLEX believes that yet stronger reasons remain for continuing to explore Earth's neighbors in space.

Contemporary planetary scientists strive to answer questions akin to those that have perplexed scientists, philosophers, religious leaders, and lay people since ancient times: What are the planets like? How did the Earth, Sun, Moon, and planets come into existence? What are the laws and physical processes that shaped the past evolution of Earth and its sister planets and govern their behavior today? How did life arise on Earth, and, more significantly, is it unique? With the growth in scientific knowledge over the centuries, the questions have certainly changed in emphasis; for example, 400 years ago, few would have used the phrase "solar system" or asked about its evolution. A basic reason for asking these questions is curiosity, but the answers often benefit humanity in both intellectual and applied ways.

The questions posed above are truly fundamental, but many scientific disciplines—from particle physics to molecular biology—deal with questions of similar importance. What other attributes might give planetary studies and space research additional significance from a national perspective? Some maintain that the exploration of the solar system brings significant societal benefits: through this high-technology venture, engineering sciences are stimulated, education from kindergarten through graduate school is enriched, the stature of our nation is enhanced, and justifiable pride in the adventurous nature of the human spirit accrues to spacefaring people.

SCIENTIFIC GOALS

The broad scientific goals for solar system exploration are to:[1]

- Understand how physical and chemical processes determine the main characteristics of the planets, thereby illuminating the workings of Earth;
- Learn how planetary systems originate and evolve;
- Determine how life developed in the solar system and in what ways life modifies planetary environments; and
- Discover how the simple, basic laws of physics and chemistry can lead to the diverse phenomena observed in complex systems.

Comparative Planetology

A major motivation for much solar system research is to understand, in quite general terms, the manner in which planetary bodies function as distinct classes of objects. Various scientific disciplines—geology, meteorology, and space plasma physics, for example—once pertained solely to Earth. Now they are enriched by being studied in the broader context of the whole solar system rather than just one body. Although this comparative approach has often been greatly overstated, this report makes clear that substantial advances in understanding are being realized by investigating planetary processes as they apply in different settings.

The scientific method involves the recognition and formulation of a problem, the collection of data through observation and experimentation, the development of quantitative theories that make use of the most advanced physical, chemical, and mathematical knowledge, and the testing of these theories against the available data. In times past, in studies of Earth—an exceedingly complex body—systematic application of the scientific method was hindered because, with only a single object on which to collect data, hypotheses could rarely be tested in as general a way as would be desired.

Now with the information gathered at other planets, we can see whether mechanisms that appear to successfully explain terrestrial processes are also valid in different planetary circumstances. For example, since Mars and Earth have similar values of spin rate and axial tilt, we might test how important these quantities are to daily weather. Similarly, we might investigate the relative importance of various energy sources (solar radiation, internal heat, condensation, and so on) in driving weather. A start on this problem can be made by noting that Venus absorbs solar heat at a rate comparable to Earth; in contrast, internal sources, plus energy release through condensation of volatile species such as water, fuel the atmospheric motions of the giant planets.

Much of our knowledge about planetary processes derives from concepts that were first applied only to Earth. Planetary investigations of bodies that evolved under conditions far different from those present on Earth provoke us to develop a deeper and more general grasp of natural terrestrial phenomena, as well as to achieve a more confident understanding of Earth's history.

As our studies of Earth and the other planets proceed, and our understanding grows, we have an opportunity to try out our skills and models on a variety of similar problems. The case of Earth's ozone hole illustrates the point. The modeling techniques used to study stratospheric photochemistry were first developed 30 years ago to understand Earth's lower thermosphere and middle atmosphere. Ten years later they were applied to Venus and Mars. Finally, when the Antarctic ozone hole was discovered, the modeling techniques were used to assess the effects of chlorofluorocarbons, NO_x, and HO_x on terrestrial stratospheric ozone. The success of these models in explaining the makeup of the upper atmosphere of our planetary neighbors built confidence in the validity of these models, and that confidence is very important when considering systems as complex as Earth.

Many provocative ideas in terrestrial atmospheric sciences—nuclear winter, ozone depletion through fluorocarbon chemistry, and greenhouse warming by CO_2—were stimulated by complementary ideas being pursued in the planetary sciences. By exposing circumstances in which concepts based on terrestrial analogs fail, planetary investigations help us define the limits of applicability of these Earth-centered ideas. The realization of the importance of catastrophic impacts on Earth in recent geological epochs, and an assessment of the present threat they pose to life on our planet, rely heavily on the study of cratering rates in the solar system and especially on observations of the near-Earth objects likely to strike our planet.

Solar System Origin and Evolution

A profound question for scientists, philosophers and, indeed, all humans concerns how the solar system originated and subsequently evolved. To understand the solar system's formation, it is necessary to document fully the chemical and physical makeup of its components today, particularly those parts thought to retain clues about primordial conditions and processes. These primitive materials are most likely found on relatively unaltered bodies—asteroids and comets—as well as in the meteorites and dust grains that are fragments of these objects.

To supplement the available data about origin in the solar system, significant information about the birth of planetary systems comes from theoretical modeling and observations of star-forming regions across the galaxy. These studies have a synergistic relation with astrophysics. During the last decade, important measurements of the environments of stellar nurseries have been made at infrared and radio wavelengths; these observations show that disks of orbiting material are ubiquitous around stars in the process of formation. Numerical simulations demonstrate that planets can readily grow in such environs.

Perhaps the most critical element yet missing from a complete picture of planetary growth is the ability to scrutinize other planetary systems that are similar to our own. Recently a compact "planetary system" was discovered around a millisecond pulsar; the constituent "planets" have orbital characteristics and masses like Earth's inner siblings and the Moon, but their surroundings are quite unlike those of our solar system.[2] The apparent birth of this system in such an implausible setting supports the notion that planetary formation is easy; if it is, the Earth is unlikely to be unique as a habitable abode.

Our ignorance of the variety of planetary systems is similar to that which pertained to the earth sciences before the advent of the important concept of comparative planetology, discussed in the previous section. Theoretical and observational understanding of other planetary systems will be essential to appreciating how our solar system formed and operates.

Life on Earth

Even if we could demonstrate an abundance of extrasolar planets, the fundamental issue—Are we alone?—would remain unanswered. This issue underlies the third scientific theme of the planetary exploration program. The goals in this area are to determine whether life (complex or primitive) exists, or once existed, elsewhere in the solar system or the universe; to identify the physical conditions and the chemical components that led to life on Earth and whether these conditions can be found in other locales; and to appreciate the influence that life has had on the terrestrial environment.

Questions about the origin of life involve all the "hard sciences." To understand how life on Earth could have begun, and how that information may be extrapolated to other astronomical settings, we must know the ambient environments in which terrestrial organisms first arose. Hints as to these conditions may be garnered from telescopic observations but also may be calculated by applying well-known physical laws.

Commonplace chemical processes are thought to have generated complex organic molecules that provided appropriate starting points for the genesis of life. Biochemistry and biophysics, of course, play central roles in the evolutionary path that produced humans. It has been shown that individually some of these steps leading to the origin of life are easily accomplished; however, the synthesis is not so easy.

Life, especially in the form of humans, has had—and continues to have—a profound influence on Earth. Some are convinced that the human species threatens the health of the planet, but current understanding of the terrestrial ecosystem and of the workings of our planet is insufficient to decide whether such a claim is valid. This uncertainty gives an urgency to studies that place the operation of Earth's physical and chemical processes in a broader scientific perspective.

Natural Laboratory for Large-Scale Physical and Chemical Processes

The examination of physical and chemical phenomena occurring in the solar system strengthens our overall understanding of the behavior of natural systems. This is true for two interrelated reasons. First, it is always valuable to test the validity of scientific theories under extreme conditions, and the solar system provides a wide range of circumstances. Second, each component of the solar system is a complex, interacting entity subject to many competing forces; thus it is crucial to compare the resultant fates of these objects if we are to comprehend fully the pertinent physics.

The solar system, and indeed the universe, have been shaped by complicated interconnected processes that unfortunately cannot be easily investigated in isolation from each other. While theorists can, of course, speculate about what happens in physically complex situations, actual tests of many important mechanisms cannot be carried out in terrestrial laboratories. Experimental validation is absent either because spatial dimensions or time scales are too large or because certain parameters (e.g., particular plasma environments or high pressures) cannot be achieved in terrestrial laboratories. Frequently, however, such phenomena can be investigated by direct observations of solar system objects. For example, the giant planets provide data about the properties of matter under extreme pressures; planetary magnetospheres show processes that accelerate particles to high energies; and the atmospheres and surfaces of planets and satellites display possible outcomes for the evolution of complex systems.

Processes invoked in astrophysical models frequently have no terrestrial analogs. However, in at least a few of these cases, similar situations occur somewhere in the solar system. Possible examples include parallels between plasma acceleration mechanisms in pulsars and in the jovian magnetosphere; connections between wave generation seen in planetary rings and in spiral galaxies; and dust obscuration of cometary nuclei and star-forming regions. Detailed observations of these environments may thus yield valuable insights pertinent to the distant reaches of the universe. In this way, wide-ranging investigations of the neighboring planets will continue to be the foundation on which is built much of our understanding of natural phenomena throughout the universe.

NONSCIENTIFIC GOALS

> We shall not cease from exploration, and the end of all our exploring will be to arrive where we started and know the place for the first time.
>
> —T. S. Eliot

The American public supports solar system exploration for reasons that sometimes differ from those of the scientist. Some of the nonscientific arguments include the inspiration of adventure and exploration; the encouragement of science education; technology stimulation; and enhancement of national pride, prestige, and security. COMPLEX recognizes that many of these issues are emotionally powerful mantras and that an honest and rigorous analysis of their validity is beyond the competence of a committee selected on the basis of its expertise in the planetary sciences. It is, however, useful to place the scientific reasons for planetary exploration into a broader context while not explicitly accepting or rejecting the validity of any of the nonscientific motivations.

Inspirational Challenge of Exploration

Some claim that space exploration is a romantic activity in a world where romance has almost vanished. Planetary images returned by our robotic emissaries turn fuzzy lights in the night sky into new worlds immediately accessible to all. In contrast to their parents' vague ideas of the solar system a mere quarter century ago, children today comprehend the barrenness of the volcanic plains of Mercury and the similarities of Mars to Earth.

Among the most fundamental of human drives are the urges to know and explore. For some individuals these urges result in merely wondering what is around the next bend in the path; for others they ignite hope for personal glory or reward through recovery of natural resources. But, in events of historic proportions, these urges have resulted in, for instance, the diffusion of our hominid ancestors from Africa's savannas, the movement of Asiatic peoples across the Bering Bridge during the last ice age, the voyages of Europeans in longships and caravels earlier this millennium, the exploits of the Lewis and Clark expedition, and continuing exploration of the oceans' depths today.

For some, the romance of space is intimately tied to piloted spaceflight, and the Moon and Mars are the obvious targets for future programs of human exploration. These bodies are among our nearest neighbors, and Mars is the most Earth-like planet in the solar system. But, as the Space Studies Board's Committee on Human Exploration has maintained, even if an ultimate goal of the nation's space program is to place astronauts on the surfaces of the Moon and Mars, precursor robotic missions to these locales will be required in order to characterize their environments.[3] Furthermore, there may be reciprocity: some science goals may be accomplished—or enabled—by manned flights and planetary landings.[4]

In most cases, robotic planetary probes currently provide the most efficient and safest way to extend the human presence. Now the average person is able to be an arm-chair explorer, whether watching a spindly robot saunter into a seething volcano or an automated submersible glide up to a hydrothermal vent in the ocean's depths. In many ways the Earth's solar system siblings form the last frontier. Television audiences worldwide have walked with astronauts across desolate lunar valleys, skimmed over the ocher-tinted cloud tops of Saturn, and sailed past cantaloupe-skinned Triton. No longer is planetary exploration the exclusive preserve of the specialist steeped in arcane knowledge—all who care to can participate at whatever level they desire.

Some sociologists assert that the American drive to explore and exploit the West was instrumental in developing a unique national character—the ability to respond to challenges, to take risks, to discover new solutions to old problems—that led to world leadership in the middle of the twentieth century. The supposition argues that further exploration is needed to stimulate our society so that the United States can keep and maintain its special identity.

The challenge of exploration is one of the principal reasons for considering a mission to study Pluto and Charon. Recent telescopic observations have revealed the basic physical characteristics of these two bodies, but until this system is visited by a robotic spacecraft, Pluto and Charon will remain as tantalizing reminders of unfinished business on the edge of the solar system.

Stimulation of Technology

At the end of the eighteenth century, Adam Smith argued that the wealth of nations lay in their trade. Today, many believe that a society will thrive economically only through its technological prowess. The exploration of distant planets by sophisticated spacecraft places many demands on engineering skills. To reduce launch weight, instruments must be miniaturized. To transmit significant information from great distances, data compression schemes and safeguarding algorithms must be devised, while sensitive receivers must also be developed. To yield information after many years of exposure to the rigors of space, long-lived reliable components, especially electronics, must be designed. To permit efficient exploration, microrovers and telerobotic devices need to be perfected. Simply put, the scientific goals of planetary and lunar missions create technical and engineering hurdles that are valuable stimuli for any society. Some would argue, however, that the technology derived from the exploration of the solar system is only likely to be widely beneficial if the exploration is pursued in such a manner that the technological thrusts developed are timely.

Education

It has been said that the main "scientific" interests of school children are dinosaurs, ghosts, and space. Of these three, the first are extinct, and the second never existed; only the third is real today. Many students, from kindergarten to graduate school, are excited by space exploration and may thereby be attracted to science and engineering careers. Through space missions, students can appreciate the importance of engineering achievements and technical solutions and can see firsthand that engineering is a challenging and rewarding intellectual activity, not a set of dry formulae.

Many trace the popularization of the environmental movement to the first Apollo views of blue-marbled Earth isolated against the austere blackness of space. This perspective and the realization of the fragility of the terrestrial ecosystem are, to some degree, outcomes of the space program. Important technical issues, like ice ages, nuclear winter, life-threatening impacts, and greenhouse warming, have been illuminated for the general public by planetary comparisons.

National Pride, Prestige, and Security

Some experts contend that the U.S. space program, especially the nation's rush to land a human successfully on the Moon, developed as an outgrowth of the Cold War. They argue that space exploration was used as an instrument of national policy to convince the world that U.S. capitalism was superior to Soviet communism. During the Cold War, national security was a function of the number of divisions in a country's army, aircraft carriers in its fleet, and bombers in its air force. These issues have limited current relevance. As a new world order emerges from the dust of the Berlin Wall and the fragments of the Soviet Empire, we must seek a new definition of national security, perhaps in terms of economic competitiveness, retention of technological capabilities, and the flexibility of our governmental, industrial, and educational institutions to adapt to a changing environment. Much may be unfamiliar, but in a world where economic factors may largely determine the long-term prosperity and security of any society, the space program will be just as visible and persuasive an advertisement of U.S. technological superiority as it ever was.

Understanding the Universe and Our Place in It

One constant since humans gained consciousness has been the quest for understanding who we are and where we came from. Are we unique or commonplace? Are we exalted beings or merely a crude way station in a long evolutionary chain? To address these profound questions, we need to know how planets form and how life originated on Earth.

Whether or not the search for life elsewhere in the universe is successful, the quest alone has significant philosophical and religious ramifications. If extraterrestrial life is found, or similarly if it is shown that life develops easily, our self-perception will be altered. Conversely, if the pursuit remains unsuccessful or if experiments convincingly demonstrate the difficulty of producing biological entities, we will emerge wiser people, reinforced in the need to preserve "this fragile Earth, our island home."

CONCLUSIONS

This nation might decide to emphasize one or another of the above motives—whether scientific or national policy—in designing a program for the exploration of the Moon and the planets. Naturally, slight changes in emphasis among the factors discussed above will result in quite different programs. Many scientists would argue that attempts by the National Aeronautics and Space Administration or others to justify exploration of the solar system primarily on the basis of goals other than exploration and inquiry are ultimately self-defeating. If what is done is not good exploration and inquiry, they maintain, then the program will also not produce spinoffs effectively. On the other hand, COMPLEX finds it difficult to justify a federal expenditure on space science that roughly matches the budget of the National Science Foundation unless the nation derives additional benefits from the space science program. What those additional benefits might be is beyond the competence of COMPLEX to judge. It is clear, however, that whatever emphasis is given, it should be the result of a conscious national decision reached after extensive public debate.

Planetary exploration represents a powerful goal for our nation. Recent successes, as well as failures, point out the potential, but also the fragility, of this endeavor. Viewed from the perspective of hundreds of thousands of years of human existence on this planet, the progress we have made in planetary exploration in the last few decades has been truly astounding. The bountiful knowledge gathered to date will serve as a springboard for planning and accomplishing the next steps in our efforts to explore and understand the solar system.

Because COMPLEX's expertise lies primarily in the scientific aspects of planetary exploration, the committee hereafter focuses its attention on surveying the present state of our understanding of the solar system, identifying the major gaps in our knowledge, and prioritizing how best to achieve the next advances in exploration.

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2

Framework for Strategy

In this chapter COMPLEX presents many of the background details of its integrated strategy. In particular it gives arguments for—and against—setting scientific priorities, recalls the nature of the committee's past advice, discusses COMPLEX's approach to—and assumptions used in—setting priorities, and outlines the remainder of the report.

SETTING PRIORITIES

Choices must always be made, whether in one's personal life or professional domain. In the scientific arena, a variety of arguments can be made as to why choices should—or should not—be made by scientists. Many of these arguments were explored in depth by the Space Studies Board's Task Group on Priorities in Space Research, and in this chapter COMPLEX draws heavily from that group's report.[1]

Arguments for and Against Setting Priorities

Among the positive arguments for setting priorities in science are the following:

- *If scientists don't act, others will.* The imagination and ingenuity of scientists far outreach what can be supported with the resources available for planetary research. Thus, selection of what can—and cannot—be done is inevitable. Scientists are the best qualified to ensure that only activities of the highest scientific merit are chosen. If scientists cannot or will not make these choices, then other people with different agendas will do so.

• *Consensus is compelling.* The complex interplay of many competing factors, only a few of which are scientific, determines which planetary science projects are performed. If a scientific community is united behind a common set of priorities, then it is easier to ensure that scientific merit is the deciding factor.

While such arguments can be marshaled for setting priorities, as many, if not more, can be raised against prioritization. An examination of each of them, however, reveals flaws.

• *There will be losers.* In any prioritization there are always winners and losers. The important question is what criteria are used in the selection process. Better that the choice be made on the basis of scientific importance rather than, as is all too often the case, factors having little to do with science.

• *Setting priorities is too difficult.* Setting priorities *is* difficult and time-consuming, and most researchers would rather spend their time doing science. But, as argued above, if scientists do not set priorities, others will, for reasons having little to do with scientific merit, and that in the longer term will cause greater difficulties.

• *Priorities cannot be maintained.* Some scientists may attempt to subvert the prioritization process if their projects are not highly rated. Rather than lobby for projects judged to be inadequate by their peers, such scientists should direct their efforts to devising more exciting proposals.

• *Setting priorities is counterproductive.* An argument can be made that setting priorities is so fraught with difficulty that it will fragment the scientific community and that the resulting harm will far outweigh any benefits. Although this could be true if the prioritization process were not conducted by established groups, using known criteria, and with the participation of the wider community, such an argument implies that the planetary science community is too immature to govern itself, and it invites prioritization by external bodies.

• *Low priorities will be abandoned.* Poorly rated activities in a list of priorities present policy makers and politicians with tempting targets for elimination. But if the prioritization is performed by the research community using scientific criteria, then it is better to forgo doing projects of low merit rather than those of high merit.

• *Scientists cannot make political judgments.* Scientists can make scientific judgments, but they are less qualified to comment on the social, political, and budgetary factors that play major roles in determining which projects are funded and which are not. There are two possible responses to this comment depending on the type of prioritization being performed. If scientific questions are being prioritized, with no implied mode of implementation, then there is little need to consider budgetary and other factors. On the other hand, if the prioritization scheme does specify implementations for which public funds will be required, then scientists have an obligation to develop and justify a set of priorities that is cost-effective in terms of anticipated return for the expenditure.

Appropriateness of Setting Priorities

Given these arguments and counter-arguments, scientific committees are still reluctant to assign priorities among alternative scientific projects, and for good reasons. It is essential to the healthy progress of science that parallel advances are made in the various areas of specialty, so that timely, mutual interaction between disciplines and subdisciplines will take place. In addition, it is necessary that a wide range of opportunities continue to be available to young scientists, so that the planetary science community will continue to possess the breadth that is one of its greatest strengths.

For this reason, COMPLEX believes that it is improper for it to make priority judgments for "small science" research projects, of the sort principally supported by modest grants from the research and analysis program, and observing programs. For research at this level of cost, adequate mechanisms for ensuring quality are in place: periodic peer review of proposals and scientific publications, whereby the quality and productivity of individual scientists are evaluated.

Even for large projects that require major or long-range commitments of public funds, reports of the National Research Council and NASA scientific advisory committees have often emphasized the need for balanced programs, rather than, for example, emphasis on missions to a particular class of bodies in the solar system in preference to all others. At the same time, COMPLEX recognizes, particularly at a time of limited opportunities for any new ventures, that decisions must be made between proposed new projects. These decisions cannot be based purely on scientific grounds (see Chapter 1), but COMPLEX believes it is obliged to help provide the scientific component of this decision-making process. Indeed, given the committee's composition and expertise, scientific excellence is the only area in which it has special competence.

PAST COMPLEX REPORTS

COMPLEX has traditionally set scientific priorities for limited subsets of solar system objects or for narrowly defined aspects of the planetary sciences. Over the past 15 years, COMPLEX has published a series of reports covering the inner solar system,[2,3] the outer solar system (but emphasizing Jupiter and Saturn),[4] primitive bodies,[5] and extrasolar planetary systems.[6] Progress toward these goals was assessed in 1991.[7] The latter report also covered advances made in achieving the scientific objectives for studies of the origin of life set forth by the Space Studies Board's former Committee on Planetary Biology and Chemical Evolution.[8] Following the dissolution of that committee, its responsibilities devolved to COMPLEX.

These documents are, to differing degrees, somewhat dated because of rapid advances, improved understanding, and new capabilities. Moreover, at the time some COMPLEX reports were written, very little was known about certain objects. Thus, COMPLEX's past strategies are incomplete, particularly regarding the outer solar system, since Voyager had not yet visited Uranus and Neptune when the 1986 outer-planets strategy was prepared. Nor had Pluto and Charon undergone their revealing series of eclipses and occultations. This report attempts to fill these gaps, but it does not replace the reports referenced in the last paragraph. Rather, unless stated otherwise, COMPLEX reendorses its past recommendations for lunar and planetary exploration. The current report should be regarded as a framework for viewing the planetary sciences as a unified whole and for setting past recommendations in their relative scientific priority.

APPROACHES TO PRIORITIZATION

Given the incentives to prioritize, what approaches have different scientific communities taken? Is COMPLEX's traditional approach the most suitable? That taken by the astronomy and astrophysics communities might be thought to be particularly relevant given the significant overlap among its tools, techniques, and interests with aspects of the planetary sciences.

Each decade, for the last 30 years, U.S. astronomers have set forward their future plans and priorities. Beginning in 1964 with the work of the Whitford Committee[9] and continuing with that of the Greenstein Committee[10] in 1972, the Field Committee[11] in 1982, and, most recently, the Bahcall Committee[12] in 1991, these influential reports have charted the future path of ground- and/or space-based astronomy in the United States.

The first, and most obvious, comment to make is that the decadal reports' approach is fundamentally different from that traditionally used by COMPLEX and the Space Studies Board's other committees. The approach taken by the SSB is to devise scientific strategies that define current knowledge and then pose and prioritize the most important scientific questions that remain unanswered in a particular discipline. Thus, these strategies are not implementation plans and are, in fact, independent of the means of implementation.

In contrast, the astronomers' decadal reports are implementation plans responsive to the widely held, but unwritten, scientific priorities of the astronomical community. In other words, they prioritize in terms of projects and initiatives designed to address a broad range of community goals rather than particular scientific questions.

Having considered alternative modes of prioritization, COMPLEX reiterates its belief that the SSB's traditional approach of prioritizing scientific goals is the most appropriate, given its areas of expertise. COMPLEX further reaffirms that prioritization of the means by which its scientific goals are achieved is best left in the hands of the appropriate internal NASA committees.

A study of past COMPLEX reports reveals that the goals for the planetary sciences are many and varied. Virtually every object in the solar system has something unique to tell us about important scientific questions. Thus, it could be argued that the best way to devise an integrated strategy for the planetary sciences is to consider each planetary body and prioritize the most important scientific questions for that body. Such "shopping lists" make life much easier for mission planners. If, for whatever reason, NASA decides to send a mission to, say, Mercury, all that is needed is to look at the appropriate shopping list to choose the scientific investigations.

Such an approach may have been appropriate in the early phases of solar system exploration when very little detailed information was known about any particular object. But with the initial spacecraft reconnaissance of the solar system drawing to an end, the situation is very different. Now we have good information about a few objects (e.g., the Moon, Mars, and Venus) and have very poor information on others (e.g., comets, asteroids, and Pluto). While most other planetary bodies fall somewhere in between these extremes, we can expect much new data about Jupiter and Saturn from the Galileo and Cassini missions, respectively, in the next 15 years. With some gaps existing, an obvious temptation is to attempt to fill them all at the expense of everything else, that is, to emphasize cataloging and categorizing rather than hypothesizing and comprehending.

Rather, we must frame the priorities to guide the next phase of solar system exploration in terms of the scientific knowledge and insights resulting from more than three decades of efforts. We can no longer treat individual planetary bodies in isolation; instead we must try to understand their similarities and differences. Why, for example, do Earth and Venus, two terrestrial planets with similar gross physical properties, have such different atmospheres? Why is the principal constituent of one of these atmospheres (Earth's N_2) the same as that of the atmospheres surrounding Pluto and the satellites of two of the giant planets?

An extreme approach to prioritization would be to list every important remaining question for which answers are needed and attempt to rank them according to their scientific importance. Such an approach would be daunting, if not impossible. How do you determine the relative priority of measuring, say, rare-gas isotope ratios in Venus's atmosphere and crater densities on Pluto? Even if such a list could be devised, it would be useless for any practical purpose because it ignores the discrete nature of planetary bodies (i.e., engineering realities usually dictate that missions can only easily stop at one object). How, for example, could you design a mission responsive to the highest scientific priorities when those priorities might encompass very different objects in widely separated parts of the solar system?

Thus, a practical prioritization scheme must recognize both the discrete nature of planetary objects and the underlying physical processes that create their similarities and differences.

In summary, COMPLEX's approach to prioritization is to:

1. Maintain the Space Studies Board's approach of prioritizing scientific objectives rather than "missions";
2. Prioritize scientific questions of significance to the whole of the planetary sciences rather than to just localized regions of the solar system; and
3. Maintain realism with regard to such practical matters as cost, technical feasibility, and the discrete nature of planetary bodies.

The perceived scientific importance (point 2 above) must always be appropriately balanced against the likelihood that significant measurements can be achieved with current or reasonably foreseeable techniques.

WHAT ARE THE ASSUMPTIONS?

The space program is always in a state of flux for a variety of reasons, including redirected federal budgets; failures in launch, spacecraft, or instruments; technological advances; and changing scientific emphasis. It is worthwhile reviewing a few historical precedents to learn how each of these factors has influenced planetary exploration and to see if we can extract any lessons for the future.

Changing national policy goals can have a profound effect on the resources available for the exploration of the solar system. A prime example is the rapid increase in the funding for space exploration (both human and robotic) following President Kennedy's initiation of the Apollo program in 1961. The precipitous drop in space funding following the termination of the Apollo program in the early 1970s is another.

A more recent, but less general, example of the profound effect the political climate can have on long-established scientific priorities is evident in the termination of the Comet Rendezvous Asteroid Flyby (CRAF) mission in 1992 for budgetary reasons. CRAF was not the first mission to be canceled, and it probably will not be the last. Even though programs such as the Ranger lunar orbiter, the Voyager martian lander, the Grand Tour, and the Venus Orbiting Imaging Radar were canceled, many, if not all, of the scientific goals of these programs were achieved by the Lunar Orbiter, Viking, Voyager, and Magellan missions, respectively. The lessons to be learned may be to never place too much emphasis on the particular implementation of a set of science objectives, and to be prepared to perform creative repackaging of those objectives as the external environment dictates.

A related issue concerns opportunism. Changing circumstances, be it the success of one planetary mission or an administration's emphasis on, for example, advanced technology, may create political momentum for other missions. Some commentators have observed that the planetary science community has not been adept in taking advantage of such opportunities.[13] Past examples that have been mentioned by some commentators include the failure of the planetary science community to support the flight of a Viking spare back to Mars or a Galileo spare to Saturn. Current examples might include the nonscientific pressures favoring a Pluto mission and the opportunities arising from potential scientific participation in technology missions such as the Department of Defense's Clementine[14] mission and proposed 4-meter space telescope.

Another factor influencing space exploration, which should be borne in mind when setting priorities, is the fact that it is of necessity a complex and technically challenging activity. Not surprisingly, therefore, mishaps and accidents occur. These can lead to total failures such as Rangers 1 to 6 and Mariners 1, 3, and 8, or partial failures such as Galileo's jammed antenna or the Hubble Space Telescope's once-blurred vision. Complete failures, as we have seen with Mars Observer, are far from a thing of the past. A repeat of such an occurrence, or worse still, the failure of a billion-dollar mission, could have a potentially devastating effect on the political support for planetary exploration and on the morale of the planetary science community.

The priorities of space exploration are also subject to increasing scientific understanding and even changing scientific fashion. At one time, for example, measurement of the hydrogen/helium ratio in the atmospheres of the giant planets was given highest priority.[15] Now that it is roughly known, its importance in constraining origins has been devalued. Given the long lead times associated with mission planning and instrument selection, changing scientific priorities can lead to the selection of an instrument or suite of instruments that is scientifically obsolete by the time of the flight. Rapidly advancing technology can also lead to prelaunch obsolescence, especially when programs are delayed for long periods. These problems argue strongly for short mission-development schedules (achieved, in appropriate cases, by the use of small, relatively cheap spacecraft) and for frequent reassessment of past priorities.

It is important, at this point, to recall that the three phases of planetary studies, reconnaissance (identification of major characteristics—typically by flyby missions), exploration (systematic discovery and understanding—typically by orbiter missions), and intensive study (in-depth pursuit of sharply formulated, specific problems—typically by atmospheric probes or lander missions), do not stand alone.[16] This report, like previous COMPLEX strategies, promotes systematic investigations in which data and understanding resulting from initial reconnaissance and exploration lead eventually to intensive study. Thus, a break in the logical progression of missions, whether due to cancellation or a failure of one sort or another, will usually require that the lost mission, or an improved version of it, be reflown.[17]

This current strategy assumes that certain ongoing or approved space missions and other activities either are successful or will continue as planned. The following sections discuss these missions and activities.

Galileo

The ongoing Galileo mission, consisting of an orbiter and atmospheric entry probe, will arrive in the jovian system in December 1995 and will perform intensive studies of Jupiter's atmosphere, satellites, rings, and magnetosphere. Even though the spacecraft is handicapped because of the failure of its high-gain antenna to unfurl, the breadth of the baseline science has been maintained; however, its depth has been compromised. Galileo will return the full data stream from the atmospheric entry probe (released prior to orbital insertion) to the 20- to 25-bar level in the jovian atmosphere. It will also return many high-resolution images and spectral observations of the Galilean satellites (obtained during multiple close approaches) and most of the planned magnetospheric observations, although at considerably lower resolution than the baseline mission would have provided. The remote-sensing observations of Jupiter's atmosphere will be limited, with measurements pertinent to atmospheric dynamics suffering the greatest damage.

The baseline Galileo mission was designed to be responsive to COMPLEX's objectives of determining (1) the chemical composition and physical state of Jupiter's atmosphere, (2) the chemical composition and physical state of Jupiter's satellites, and (3) the topology and behavior of the magnetic field and energetic particle fluxes.[18] However, NASA assigned equal priority to each of these objectives, whereas COMPLEX ranked them in the order shown.

Although Galileo will vastly improve our understanding of the jovian system, we know even now that it will leave many important questions unanswered. Even the baseline mission would not have addressed priority issues concerning Io, the inner magnetosphere, and the planet's polar regions.

Cassini

The approved Cassini mission, consisting of an orbiter (supplied by NASA) and a Titan atmospheric probe called Huygens (supplied by the European Space Agency), is scheduled to enter orbit around Saturn in the early years of the next century. Once there, Huygens will carry out in situ studies of Titan's atmosphere and surface. Cassini will conduct intensive remote-sensing observations of the composition and dynamics of the atmospheres of both Saturn and Titan using optical, infrared, and (for Titan) radar techniques. In addition, it will investigate in detail Saturn's rings, magnetosphere, and retinue of icy satellites.

Cassini has been the subject of numerous COMPLEX studies and is responsive to the committee's highest priority for the exploration of the outer planets: intensive study of Saturn—the planet, satellites, rings, and magnetosphere—as a system.[19-23]

Astronomical Telescopes in Earth Orbit

The Hubble Space Telescope, a 2.4-meter optical/ultraviolet telescope located in low-Earth orbit, is, now that it has been repaired, providing unparalleled angular resolution at optical and ultraviolet wavelengths. Such capabilities are particularly suited to a number of important planetary science projects such as monitoring the atmospheres of the outer planets to provide a context for data gathered during infrequent spacecraft encounters. Even in its degraded state, the Hubble Space Telescope performed important planetary studies such as ultraviolet observations of jovian aurorae, monitoring Mars's atmosphere, and determining the individual masses of Pluto and Charon by tracking their barycentric motions.

Additional valuable planetary observations are being made by other Earth-orbiting telescopes, such as the International Ultraviolet Explorer, the Extreme Ultraviolet Explorer, and Rosat.

Major Ground-Based Facilities

Ground-based facilities have great importance to the planetary sciences. As mentioned in various sections in Chapters 3 and 4, public and private ground-based observatories have made, and will continue to make, significant contributions to our understanding of the solar system. NASA either operates or plays a major role in a number of these facilities, including:

1. The Infrared Telescope Facility, a 3-meter infrared-optimized telescope located atop Hawaii's Mauna Kea. It can achieve diffraction-limited performance at infrared wavelengths;
2. The Kuiper Airborne Observatory, a C-141 transport equipped with a 0.9-meter telescope. It can perform observations in the infrared and submillimeter spectral regions at altitudes in excess of 12,000 meters. In addition to providing ready access to wavebands inaccessible at ground-based observatories, it allows rapid response to targets of opportunity, such as planetary occultations, and complements existing ground- and space-based facilities; and
3. Keck II, a 10-meter optical/infrared telescope to be located atop Hawaii's Mauna Kea adjacent to its operational twin, Keck I. Interferometric observations using the pair of telescopes would create a potent instrument for the detection and study of extrasolar planetary systems, according to a previous assessment by COMPLEX.[24] Current plans call for NASA to partially fund the second telescope and provide interferometric instrumentation in return for a share of the observing time at this private university observatory.

Continued Support of Research and Analysis

The scientific rationale for planetary exploration is the development of understanding and knowledge. This comes not from spacecraft or even the data they return, but from scientific research and analysis of these data. Thus, NASA's research and analysis (R&A) program is *the* essential component of the U.S. program of planetary exploration. Without the scientific investigations performed by individuals and small groups supported by R&A funds, the results from robotic spacecraft and ground- and space-based telescopes could not be understood and placed in context. In fact, such glamorous projects owe their existence to the precursory studies of individual principal investigators working in their laboratories, analyzing data from existing spacecraft and telescopes, or performing complex numerical simulations.

In addition to maintaining the current generation of planetary scientists, R&A funds are vital to the future because they nurture the graduate students and postdoctoral researchers who will form the cadre of future mission planners and designers. This fragile area is falling behind. COMPLEX maintains that a vigorous R&A program is a fundamental requirement for overall success in planetary and lunar exploration.

Additional ongoing, recently completed, or approved missions that will also provide important scientific data include the following.

Ulysses

The Ulysses spacecraft was built by the European Space Agency and was launched on the Space Shuttle in October 1990. It is investigating the three-dimensional structure of the heliosphere by flying on a trajectory over the Sun's south- and north-polar regions in July 1994 and 1995, respectively. Of particular interest to planetary scientists was the spacecraft's north-south sweep through the inner jovian magnetosphere. While important data were returned, this single pass was insufficient to allow for the systematic investigations needed to address questions about the Io torus. During its time at high ecliptic latitudes, Ulysses is providing data relevant to the three-dimensional structure of the heliosphere, including the nature of the interplanetary magnetic field; the solar wind flow, density, and temperature; interplanetary dust; and the character of the energetic particle environment.

Discovery

The Discovery series of low-cost (less than $150 million) planetary missions will have limited development schedules (3 years) and measurement objectives. The first two Discovery missions—a small Mars lander called Mars Pathfinder and the Near Earth Asteroid Rendezvous (NEAR)—have been preselected by NASA and were approved in the FY 1994 budget. Future missions will be chosen by open solicitation.

Prior reports by other SSB committees have found that such small missions promote frequent access to space; support specific, well-defined scientific objectives; enhance programmatic flexibility by, for example, allowing rapid response to new discoveries; yield data not obtainable from the ground, and yet not acquired in larger missions; provide opportunities for international cooperation; and augment training for science and engineering students at universities.[25] COMPLEX has supported the Discovery concept in the past, subject to some reservations about program balance, choice of objectives, and adequate and steady funding.[26]

Given that both Mars Pathfinder and NEAR were given new starts in NASA's FY 1994 budget, COMPLEX is currently undertaking a major study of the ability of small "missions," such as those in the Discovery program, to achieve priority objectives of the planetary sciences.

Mars 96/98

Russia is building two spacecraft for launch to Mars during the 1996 and 1998 oppositions. These spacecraft will carry a broad array of internationally funded instruments, including orbiters, penetrators, surface stations, a rover, and a balloon. The orbiters will carry an imaging system, a near-infrared imaging spectrometer, and radar; the landers are expected to make mineralogical, meteorological, and seismic observations; the rover will transport imaging, mineralogical, and chemical-analysis instruments; and the balloon is planned to drift great distances while dragging a guide rope equipped with an instrument package along the ground. Although plagued by severe budgetary problems that have already caused a two-year launch delay, these missions, if successful, will contribute greatly to our knowledge of the martian environment.

Mars Surveyor

NASA's FY 1995 budget proposes a new start for a line of small Mars orbiters and landers as part of an attempt to recover from the loss of Mars Observer. Two Mars Surveyor spacecraft would be dispatched to Mars at every launch opportunity starting in 1996. Current plans call for the first few orbiters to carry spares of Mars Observer's instruments, while the landers would draw heavily on the technology developed for Mars Pathfinder. COMPLEX has not yet had an opportunity to assess their scientific potential. The initiation of this program was still in doubt at the time of this writing.

Rosetta

The Rosetta mission, the third or planetary "cornerstone" of the European Space Agency's (ESA) "Horizon 2000" strategic plan, was originally conceived as a comet-nucleus sample return mission to be conducted jointly with NASA.[27,28] Difficulties encountered in program planning, mission scheduling, technical feasibility, and cost have resulted in a number of less ambitious mission concepts ranging from comet rendezvous (with some in situ investigations of the nucleus) to multiple asteroid flybys, and rendezvous with a near-Earth asteroid. In November 1993, ESA selected a mission designed to rendezvous with, and land an instrument package on, the nucleus of a comet, either Schwassmann-Wachmann 3, Wirtanen, Finlay, or Brooks 2. Launch is scheduled for the period from 2002 to 2004. Participation by NASA is likely. If successful, Rosetta may accomplish many of the scientific objectives of the canceled CRAF.

Clementine

Clementine, a low-cost, high-risk technology demonstration sponsored by the Department of Defense's Ballistic Missile Defense Organization, was designed to test a suite of lightweight sensors (of unproven scientific merit) in a deep-space environment.[29-31] Clementine was placed in a polar orbit around the Moon on February 19, 1994. The original mission plan called for Clementine to be redirected after the lunar mission was completed and to fly by the asteroid 1620 Geographos and, if sufficient fuel remained, asteroid 1993RD. Unfortunately, a software problem disabled the spacecraft and led to the cancellation of the Geographos flyby. NASA's involvement in the mission is limited to collection and scientific analysis of the data returned by Clementine. Tentative plans exist for additional missions, including lunar landers and Mars orbiters.

In 1992, a COMPLEX assessment of Clementine concluded that the spacecraft's observations of the Moon and Geographos would provide a significant opportunity to advance our scientific understanding of these objects even though they could not satisfy COMPLEX's highest scientific priorities for lunar and asteroidal studies.[32] Given the importance of this mission as a model for future, low-cost planetary missions, COMPLEX is currently conducting an in-depth study of the lessons learned from Clementine.

INTERNATIONAL COOPERATION

At one time space exploration was the exclusive preserve of the United States and the former Soviet Union. Now it is a thoroughly international activity with a number of medium- and small-scale space powers capable of independently mounting planetary missions. The possibility of flying foreign experiments on U.S. spacecraft, and, more importantly, U.S. experiments on foreign spacecraft (such as the ongoing Mars 96/98 and ESA's Rosetta), has many advantages because it broadens the participation by the scientific community, enhances communications and develops valuable contacts, promotes the vitality of the worldwide planetary science community, and allows optimum use of limited launch opportunities.

However, international cooperation can also have drawbacks, and COMPLEX reendorses its previous recommendations that:[33]

1. Selection of foreign scientists and experiments for U.S. missions should be based on scientific merit, and the free flow of scientific data and results should be a necessary precondition for any cooperative arrangements;
2. NASA should consider all appropriate foreign capabilities available for planning and carrying out its missions and should cultivate those that enhance the scientific return; and
3. NASA should fully involve the scientific community in planning for international cooperation and in assessments of proposed cooperative missions.

While strongly advocating international cooperation, COMPLEX also reiterates its belief that such projects should not be entered into lightly. Cancellation of projects before completion not only forfeits all related benefits, but also can have a chilling effect on future cooperation.[34]

TECHNOLOGY DEVELOPMENT

The rate of future advances in the planetary sciences is strongly related to the development of innovative technology as well as to new approaches to mission planning and execution. A call for significant investments in these areas might appear obvious and be an ongoing aspect of an enterprise using some of the most technically sophisticated devices ever designed. Report after report on NASA's technology program has, however, criticized the agency's lack of investment in this area.[35,36] While NASA's attention has been wanting, the gap between the technology flown on NASA spacecraft and the state of the art (especially in such areas as computer processors and other electronic components) has grown at an ever accelerating pace. The end of the Cold War and the increasing availability of technology developed for military applications (especially the Strategic Defense Initiative[37]) give NASA a unique opportunity to substantially close this gap.

MAJOR THEMES OF THIS REPORT

As COMPLEX has already argued, an integrated approach to the planetary sciences calls for prioritization in terms of scientific disciplines and fields of study rather than a somewhat arbitrary quantity such as distance from the Sun. Thus, COMPLEX divided the planetary sciences into two major motivating themes: understanding origins and understanding planets.

Understanding Origins

The theme of understanding origins involves studies of the creation and evolution of planets and life, the search for planets around other stars, and investigations of the solar system's primitive bodies. COMPLEX has organized its discussion of these topics under four headings:

1. Protoplanetary disks around young stars that may be analogs to the solar nebula;
2. Planetary systems, both mature and in the planetesimal phase;
3. Primitive bodies, such as comets, asteroids, and interplanetary dust particles; and
4. Life originating on Earth and elsewhere.

Understanding Planets

The theme of understanding planets involves studies of the interrelated and interacting components that make up a planet. COMPLEX has organized its discussion of these topics under four headings:

1. Solid surfaces and interiors of the terrestrial planets and their satellites, the satellites of the outer planets, and the interiors of the giant planets;
2. Atmospheres of the terrestrial planets, the outer planets, and their satellites. Cometary comae are also briefly mentioned in the context of escaping atmospheres;
3. Rings of the giant planets; and
4. Magnetospheres of both the terrestrial and outer planets, planetary satellites, asteroids, and comets.

In general, the sections in this report devoted to each of these subject areas follow a similar format. Each begins by summarizing the current state of knowledge. Next there are discussions of key fields of study, subdivided in terms of important scientific themes (e.g., tectonics, climate change, or gas-dust-surface interactions with plasmas).

Each section then continues by listing key questions (in no particular order) and the measurement objectives that must be attained to make progress in understanding the relevant scientific theme. Finally, each section concludes with text entitled "What to Study and Where to Go," describing the most important studies that need to be performed and the most important planetary objects to investigate. The detailed discussions in Chapters 3 and 4 form the base on which COMPLEX determined its priorities.

A program of scientific studies, no matter how carefully devised, is useless without the necessary resources (be they ground- and space-based facilities, laboratory equipment, computers, R&A funds, and so on) to perform it. The infrastructure supporting the planetary science enterprise is the subject of Chapter 5.

In the final chapter, COMPLEX describes its recommendations for the scientific priorities for the planetary sciences in the period from 1995 to 2010. Readers seeking the basis for these recommendations are first directed to the priorities contained in the various "What to Study and Where to Go" sections of Chapters 3 and 4, and then to the extensive discussions of key questions and objectives in the same chapters.

EXPECTED AUDIENCE

In devising the strategy presented in this report, COMPLEX had several different communities in mind. In the most general terms, the first of these communities are the policy makers in Congress, NASA, and other relevant agencies and organizations. These are the people who must confront the wishes and aspirations of the planetary science community with the cold realities of national polices, priorities, and budgets. While scientific merit is but one factor in their deliberations, COMPLEX hopes that the information contained in the Executive Summary and Chapters 1 and 6 (supplemented by material from Chapters 2 and 5) will weigh heavily in their decision making. Those brave enough to dip into Chapters 3 and 4 should not be daunted by the number of questions still waiting for answers. Their number and, more importantly, their nature are testimony to the tremendous scientific return received from the billions of dollars wisely invested in the planetary sciences over the last 30 years.

The second community consists of planetary scientists in the United States and abroad who, provided that they are in agreement with at least some of COMPLEX's recommendations, will devise the means by which particular priorities identified in this report are addressed. COMPLEX believes that its priorities are diverse enough that they can be implemented by a spectrum of techniques, including theoretical modeling, reanalysis of archival data, devising observational programs with ground- or space-based telescopes, and designing small (Discovery-class), intermediate, or large missions. For this group, Chapters 3, 4, and 6 are most important.

Since this is a long-term strategy, an important community to whom this report is addressed are graduate students and postdoctoral fellows at the beginning of their scientific careers. Many of the priorities identified in this report will not be addressed by the current generation of planetary scientists. To a large degree, the difference between success and failure in research is determined by the choice of appropriate topics to tackle. Nowhere is this more important than in the early stages of a scientific career. If any of the recommendations in this report help young researchers establish their place in the planetary science community, then COMPLEX will have achieved one of its most important goals.

COMPLEX also addresses this report to itself and its successors, who will use its recommendations and priorities to assess the scientific merit of particular mission implementation plans and as a baseline for the formulation of priorities in future reports. One area where this report will be of particular use to the committee will be in assessing future missions to the outer solar systems. As mentioned at the beginning of this chapter, COMPLEX's 1986 strategy report for the outer planets has very little to say about Uranus and Neptune and almost nothing about Pluto. New information about these bodies, together with technological advances, will open a number of intriguing mission possibilities. COMPLEX anticipates reviewing these missions when they reach a sufficient level of definition.

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3

How Planetary Systems and Life Originate

The search for origins is an increasingly important focus for research in astronomy and planetary science. This interdisciplinary topic encompasses the origin of planets, stars, galaxies, and life itself. Described below is the state of our understanding and shared beliefs about:

- The environment in which our solar system and many other planetary systems were formed;
- The unique role played by the most primitive bodies in the solar system (comets and asteroids) in interpreting the record of events in the early solar system; and
- The many complex processes that subsequently shaped the planets and led in due course to life and sentient beings.

A previous COMPLEX report outlines the present understanding of the formation of our own and other planetary systems.[1] (More detailed reviews are also available.[2]) COMPLEX's report also reviewed observational knowledge of protoplanetary material and planetary systems around other stars. The report of NASA's Toward Other Planetary Systems Science Working Group provides further background on these topics and presents a three-phased plan for searching for, and characterizing, extrasolar planetary systems and preplanetary materials.[3] The Space Studies Board's former Committee on Planetary Biology and Chemical Evolution has summarized the status of knowledge concerning the history of life from prebiological epochs to the present.[4]

Given the current understanding of origins, this chapter is organized around a number of common themes or areas of study that should guide future investigations. These themes are protoplanetary disks, planetary systems, primitive bodies, and life. Within the discussion of each theme, key scientific questions are highlighted. Next, objectives in each of these thematic areas are suggested. In the final section, called "What to Study and Where to Go," the most important studies to be performed and planetary bodies to investigate are identified.

SCIENTIFIC THEMES

Protoplanetary Disks

Laboratory analysis has identified the presence of numerous extinct radionuclides in meteorites. The mean radioactive lifetimes of these species range from about 1 million to 150 million years. By comparing the production rate of these radionuclides in stellar sources (known reasonably well from astrophysical and geochemical considerations) with measurements of their abundances in primitive solar system material, we can deduce the interval between their formation and the period during which the solar system originated.

This radionuclide information, combined with astronomical data, implies that a giant molecular cloud complex developed about 100 million years before the birth of the solar system. According to current models, star formation began in the cloud complex when a large clump of gas collapsed to produce a cluster of high-mass stars. These massive stars completed their evolutionary cycle and exploded as supernovae within approximately a million years. These stellar explosions effectively destroyed the cloud complex. This process led to large-scale mixing in the local region of the galaxy and resulted in the formation of new cloud complexes and subsequent formation of other, less massive stars.

As single stars with masses between 0.7 and 8 solar masses evolve, they pass through the asymptotic giant branch (AGB) stage, which ends with the ejection of their outer envelope to form a planetary nebula. About half of the observed extinct radioactivities and isotopic anomalies seen in the tiny graphite and silicon carbide grains found in meteorites appear to be associated with AGB activity within the region of the cloud complex that gave rise to the solar system. This suggests that a particular AGB star played a role in initiating the formation of a group of new stars, one of which would become our Sun.

Radio telescopes have shown that molecular cloud complexes contain large numbers of distinct regions with high-density gas, termed molecular cloud cores. These cloud cores appear to be on the verge of gravitational collapse. Observations by the Infrared Astronomical Satellite, as well as surveys of the location of pre-main-sequence stars, show that roughly half of these molecular cloud cores have already produced young stellar objects. The existence of young stars embedded deep within molecular cloud cores is persuasive evidence for the formation of stellar and planetary systems from the gravitational contraction of dense cloud cores. If the cloud cores are initially supported by magnetic fields, this support will be lost slowly through motion of the field lines relative to the neutral bulk of the cloud, leading over millions of years to gradual contraction of the cloud core and ultimately to rapid inward collapse. However, the presence of extinct radioactivities in the early solar system (^{26}Al, for example, with a lifetime of less than a million years) implies that the presolar cloud may have been suddenly shocked into collapsing rather than allowed to evolve toward collapse in the slower, more quiescent manner associated with relative motion between the magnetic field and the gas (see Figure 3.1).

While a number of candidate objects have been observed, to date there is no commonly acknowledged example of a collapsing protostellar object. Hence our

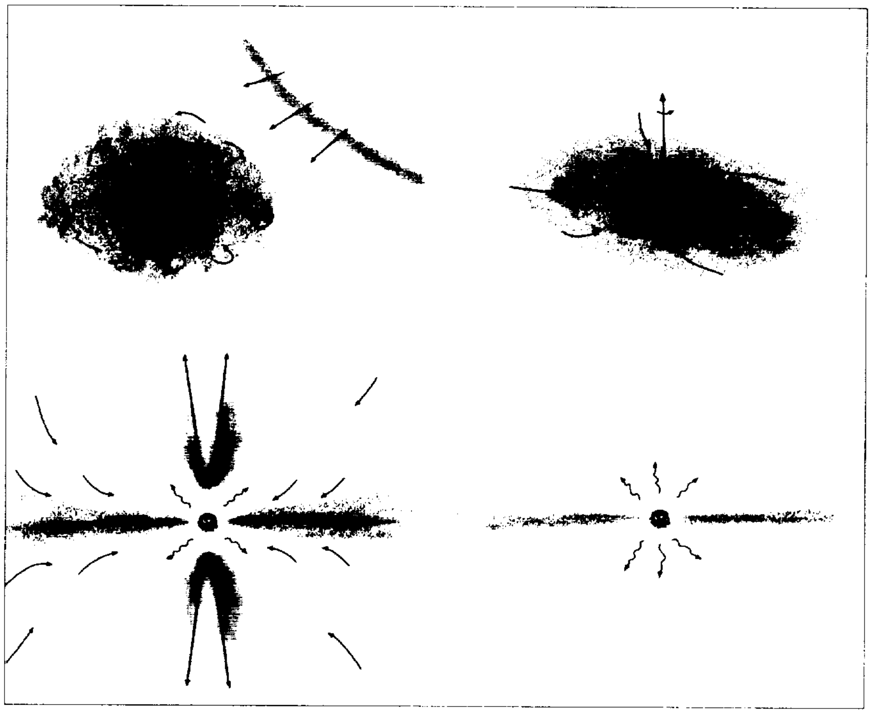


FIGURE 3.1 (top left) A dense, rotating cloud of gas (predominantly molecular hydrogen) and dust acquires presolar grains and anomalous isotopic distributions through shock waves ejected from dying stars. (top right) The dense cloud begins to collapse under its own self-gravity, largely conserving its angular momentum, and so becomes progressively flatter as it contracts and spins up. (bottom left) Low-angular-momentum matter forms the protosun, which emits a high-velocity, bipolar wind along the rotational axis. Higher-angular-momentum gas and dust fall in to form the solar nebula. (bottom right) Infall ceases, the protosun clears out the cloud envelope, and the bulk of the nebular gas accretes onto the protosun. Dust grains begin their growth through coagulation.

knowledge of the collapse phase in the formation of stellar and planetary systems relies largely on theoretical models. Radiative hydrodynamic calculations of the collapse of highly idealized, spherical protostars are in general agreement about the basic features of collapse—a compact core with a small fraction of the cloud mass forms first, and the remainder of the cloud subsequently accretes onto this core. There is also general agreement that in the more realistic case of an asymmetric, rotating cloud, collapse leads to fragmentation into two or more protostellar cores that could be the seeds of a binary star system. Somewhere between these two extremes lie clouds that collapse to form a single star like our Sun, accompanied by a rotationally flattened protoplanetary disk.

Very few calculations of the collapse of such presolar clouds have been performed. Moreover, no calculation has yet been able to follow the physical and chemical evolution of a rotating cloud all the way through to the emergence of a pre-main-sequence star surrounded by a disk suitable for forming planets. The chemistry occurring during protostellar collapse is important for understanding both the abundances of observable molecular species and the conversion of dominant interstellar species (such as CO) into the forms that predominate in the solar system (e.g., CH_4). We have considerable observational information about the properties of pre-main-sequence stars and their embedded predecessors, and even about circumstellar disks that may be in the process of forming planets. These observations include the following:

- Observations of T Tauri stars (young variable stars with masses similar to that of the Sun) show that they have strong bipolar outflows (stellar winds) indicative of collimation by, for example, a rotationally flattened disk or a magnetically driven wind;
- Millimeter-wave radiation from circumstellar dust grains and molecules has directly revealed the existence of protostellar disks in rotation about young stars;
- Young stellar objects usually emit more radiation in both the ultraviolet and infrared than would be expected from a blackbody with the temperature of the the stellar photosphere. The infrared excesses are consistent with emission from an extended disk with lower effective temperatures than the young star. The ultraviolet excesses are attributed to higher-temperature gas produced by accretion at the boundary layer between the protostellar disk and the stellar surface; and
- The infrared excesses disappear as young stars evolve, implying removal of the dust and probably the gas in the planet-forming regions within ~10^5 to 10^7 years after the formation of the system. Most of the disk mass accretes onto the central protostar, leaving a "minimum-mass" nebula in which planets may be formed.

The evolution of the solar nebula prior to the formation of planets has been divided by theoreticians into three stages:

1. The first stage begins with the formation of the protostellar core at the center of the nebula and is characterized by the infall of higher-angular-momentum matter that forms the centrifugally supported disk;

2. In the next stage the mass gained by the nebula through infall from the molecular cloud core is roughly balanced by accretion of disk mass onto the protosun. During this phase the bulk of the protosun's mass is accreted from the nebula; and

3. The final stage begins once the infall from the cloud core is terminated, either through depletion of the parent cloud core or through reversal of the infall caused by an outflowing stellar wind.

The first stage is strongly linked with gravitational collapse and so will depend critically on the initial properties of the precollapse cloud and on how collapse is initiated.

The second stage requires the existence of a dissipative mechanism for redistributing mass and angular momentum within the nebula. Three such mechanisms have been investigated to varying extents: turbulent viscosity, gravitational torques, and magnetic fields. Turbulence driven by convective instability is difficult to quantify reliably and ceases when the disk becomes optically thin, but appears to be marginally capable of driving nebula evolution on time scales short enough (millions of years) to be consistent with the ages of young stellar objects. Gravitational torques associated with density waves and other nonaxisymmetric structures can drive nebula evolution on much shorter time scales, provided the disk is sufficiently massive and cold. Magnetic fields have long been suspected to be important. However, dynamo mechanisms for generating significant magnetic fields are still in the early phases of investigation, and the degree of ionization in the densest regions of the nebula may have been too low for effective coupling of the fields and gas.

In the third stage, the rate of dissipation decreases and the matter remaining in the disk (a "minimum-mass" nebula containing about 0.01 to 0.1 solar masses) becomes available for incorporation into planets rather than the protosun.

The expertise developed by the space physics community could be of great use in evaluating the importance of magnetic stresses for solar-nebula evolution. Magnetic field lines are coupled to the ions in the nebula, which in turn are collisionally coupled to the gas. For temperatures above about 2000 K, thermal ionization (initially of potassium and sodium) would maintain sufficient ion densities for close coupling of lines, ions, and gas. At lower temperatures and densities, ionization by cosmic rays, ^{26}Al, and ^{40}K maintains a loose coupling. In a convective solar nebula, magnetic dynamo activity should enhance magnetic field strengths.

Magnetic fields in the solar atmosphere and in planetary magnetospheres are intimately involved in the acceleration and transport of plasmas. Only recently has dust been recognized as an important component of space plasmas, as found by recent cometary flybys and the observations of electromagnetic effects in the ring systems of the outer planets. These may provide a natural laboratory for the characterization and transport of charged dust and plasma in the solar nebula.

Key Questions

Key questions with respect to the protoplanetary disks include (in no particular order) the following:

- Can a true protostar be detected and characterized?
- Do binary protostars often suffer mergers through interaction with circumstellar gas and produce single protostars?
- How frequently do single stars form in protostellar disks, and what is the frequency of occurrence of residual, centrifugally supported gas and dust disks of various masses and radial mass distributions?
- Can the entire process of protostellar collapse and the formation and evolution of protoplanetary disks be modeled theoretically?
- Can we demonstrate that protoplanetary disks are capable of producing planetary systems similar to our own?
- What are the mechanisms responsible for nebula evolution? What are the temperature and surface density profiles in circumstellar disks in nearby star-forming regions?

Planetary Systems

The formation of planets begins with the agglomeration of roughly 0.1-micron-size interstellar dust grains that are processed in the solar nebular accretion shock and then accumulated into progressively larger and larger particles. Collisions between dust grains can result from Brownian motion or relative dust grain motions produced by turbulence. These collisions must, however, be very gentle if these fragile, fluffy objects are to accumulate rather than fragment. As the grains grow, gravity will cause them to sediment toward the nebula's mid-plane, and gas drag (caused by the slightly more slowly moving, pressure-supported gaseous nebula) will cause them to spiral inward. Different size particles will move at different speeds, further enhancing the chances for mutual collisions. Large objects are less affected by gas drag and, therefore, suffer little inward drift. They are thus able to grow by accumulating the smaller bodies drifting inward toward them. Throughout this sequence of events, the grains are further processed through chemical, collisional, and thermal mechanisms.

When the size of these objects reaches about 1 km, they are termed "planetesimals." The larger planetesimals subsequently grow the fastest because their greater gravitational attraction and their lower relative velocity enhance their ability to deflect smaller bodies into colliding orbits. Within about 10^5 years, these planetesimals may grow into "planetary embryos," roughly the size of the Moon or Mercury. At this point they occupy nearly circular, coplanar orbits in the vicinity of their initial location in the nebula.

Mutual gravitational perturbations cause the initially circular orbits of these runaway planetary embryos to become more and more eccentric. This means that

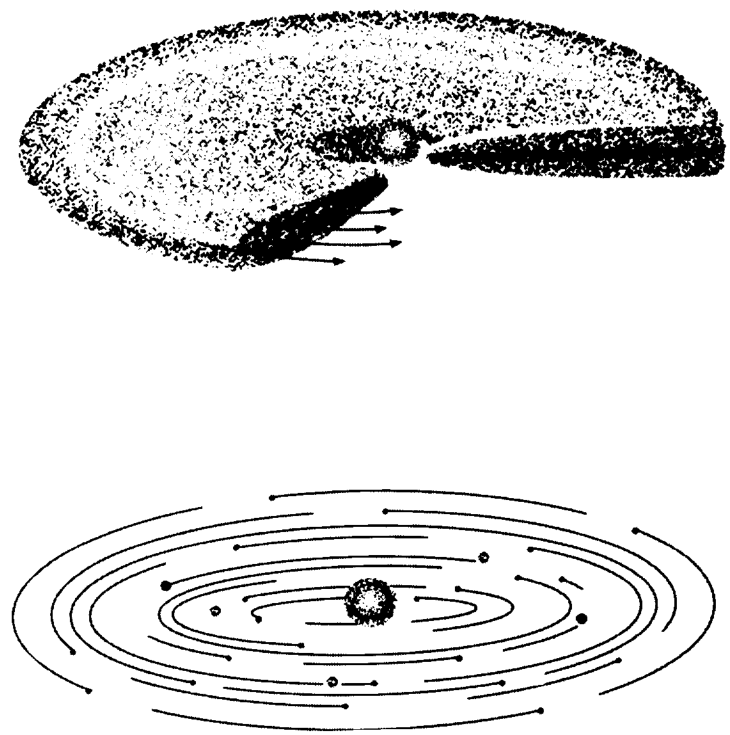
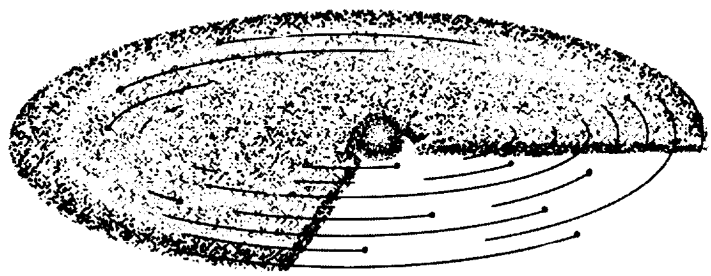
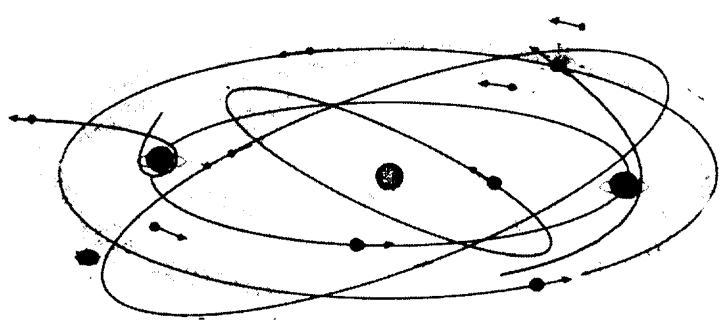


FIGURE 3.2 Possible sequence of events in the terrestrial planet region. (top left) Growth of dust grains into ~10-km-diameter "planetesimals" through nongravitational forces (sticking). (top right) Runaway growth of planetesimals, moving in nearly circular, coplanar orbits, to form ~2000-km-diameter "planetary embryos" on a 10^5-year time scale. (bottom left) Removal of gas from the inner solar system on a 10^6- to 10^7-year time scale. (bottom right) Mutual perturbation of planetary embryos into eccentric orbits and

those with different perihelia can collide. To prevent planet formation from stalling at this stage, these collisions must occur with relative velocities low enough to result in growth rather than fragmentation. The velocities, however, must be sufficiently large to avoid orbital isolation and to cause widespread mixing of embryos and residual planetesimals throughout the region now occupied by the terrestrial planets and the asteroid belt. Growth to Earth-size bodies would then occur within about 10^8 years in the terrestrial planet region, consistent with final accumulation occurring in a largely gas-free environment (Figure 3.2).

A critical step in the formation of the giant planets is thought to be the formation of objects of some 10 Earth masses prior to removal of the remaining gaseous





their merger to form the present planets on a 10^8-year time scale. Asteroids are relics of similar processes in the present asteroidal region that failed to complete the runaway growth stage (top right) as a consequence of either gravitational or collisional removal of most of the other bodies in that region. Jupiter's perturbations, beginning at about 5×10^6 years, were primarily responsible for this clearing of the asteroid belt.

portion of the nebula (Figure 3.3). For this reason, this accumulation must have occurred on a much shorter time scale in the outer nebula than in the inner nebula, in spite of the much larger orbital periods of objects located there. This process may require the growth of massive runaway embryos in the region of the giant planets. This might be possible, given a sufficient surface density of condensible solids in the outer nebula, but this has not yet been adequately demonstrated.

Theoretical models have shown that during the late phases of the accretion of the terrestrial planets, giant impacts between nearly-equal-size, planetary-mass bodies will usually occur. Giant impacts may leave a characteristic signature giving some clues to the events involved. Examples include:

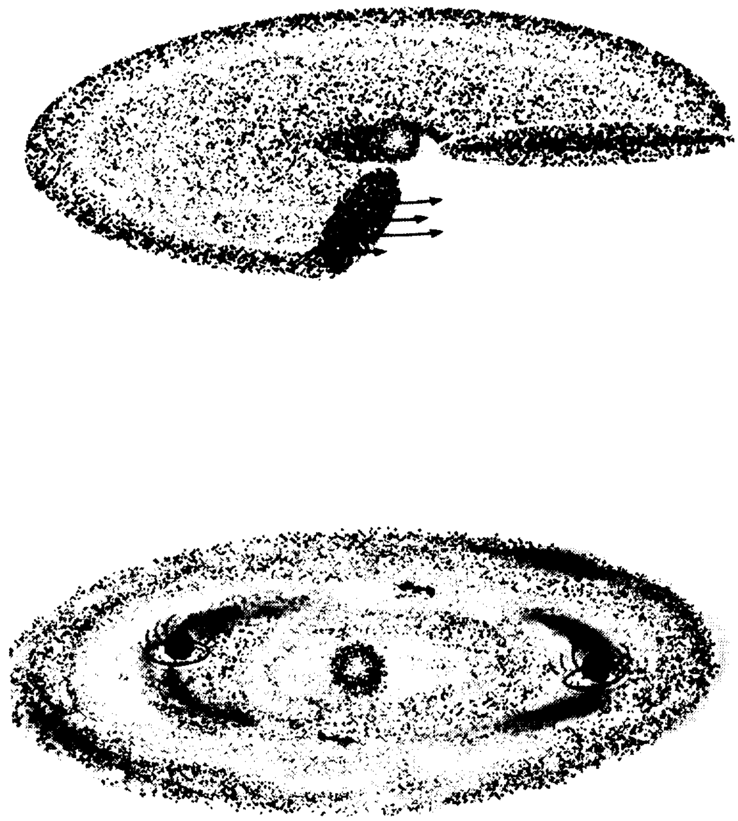
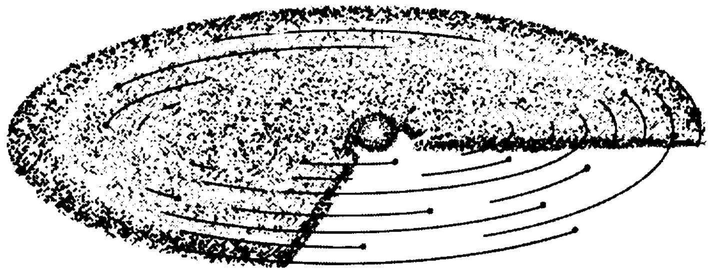


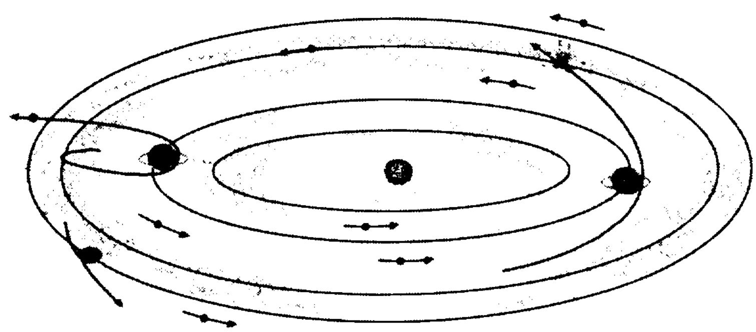
FIGURE 3.3 Possible sequence of events in the outer solar system. (top left) Growth of dust grains into 10-km-diameter "planetesimals." (top right) Runaway growth of planetesimals to form very large (10-Earth-mass) cores of the four giant outer planets on time scales of 10^6 to 10^7 years for Jupiter and Saturn and 10^8 years for Uranus and Neptune. (bottom left) Gravitational capture of nebula gas by Jupiter and Saturn on a 10^7-year time scale to form gas-giant planets. (bottom right) Comets, as well as Pluto- and Triton-like

- A silicate-depleting impact leaving the proto-Mercury with an unusually large ratio of iron-core mass to silicate-mantle mass;
- The hypothesized Moon-forming impact on the proto-Earth by an object a few tenths of Earth's mass; and
- A major axis-tilting impact of a few Earth-mass objects on the proto-Uranus.

In all three cases the impactor is destroyed.

While a giant impact on the proto-Earth is currently thought to explain the





objects, are relics of bodies in the outer solar system that failed to be incorporated into planets during the runaway growth step (top right). Most of these bodies were ejected into interstellar space by the outer planets. Residual comets were stored in the Oort Cloud (10^3 to 10^5 AU) and in the Kuiper Belt (40 to 100 AU), from which regions currently observed comets are derived.

formation of the Moon, it cannot be considered scientifically demonstrated. Hydrodynamic simulations have shown that under different impact conditions a great deal of material can be left in orbit. Many more computationally intensive simulations of giant impacts on the proto-Earth are needed, together with a better understanding of their geochemical implications, before we can understand whether or not the Earth-Moon system could have arisen through this mechanism.

Other than evidence for planetary-mass objects orbiting a millisecond pulsar and the spectacular evidence for dust disks about the stars Beta Pictoris and Fomalhaut, there are no confirmed examples of other planetary systems. The pulsar system appears to contain two objects with masses of at least 3 Earth masses in orbits with radii of 0.3 to 1 AU, and an object roughly the mass of the Moon at a closer distance. Whether or not this is a real planetary system, it has already caused theorists to reexamine the details of disk dissipation and evolution theory. If it is real, it may be an observational demonstration of the ease of planet accumulation, given a circumstellar disk that is cool enough.

The ease of planetary formation is supported by the miniature planetary systems accompanying all of the giant planets. These bodies suggest that planetary systems are likely to be common, perhaps ubiquitous, throughout the galaxy and the universe. On the other hand, theoretical modeling of the formation of our solar system shows that, in detail, the size and spacing of the planets depend on the mass and angular momentum, and, hence, the surface density of the residual circumstellar disk. The formation of gas-giant planets is quite demanding in the requirement that massive solid cores form rapidly enough to capture the principal gaseous constituent before dissipation of the circumstellar gas. It is also likely that the mass and luminosity of the central star will further affect the structure and evolution of the circumstellar disk. Even more complications will be introduced by binary and multiple-star systems.

For these reasons, although planetary systems are likely to be common, it is also probable that their variety is very great; the frequency of occurrence of habitable planets is very uncertain. On the other hand, it is conceivable that there are undiscovered, self-regulating processes that reduce this variety. Earlier theories of planet formation have emphasized explaining detailed features of the solar system. As long as we have only our own planetary system to compare with the results of general theories of planet formation, it is very difficult to know whether particular characteristics of the solar system simply represent stochastic variations or are something that the theory should be expected to predict. This difficulty is compounded by the reality that our sample of one planetary system is highly biased by the fact that it has permitted the formation of sentient life concerned with such questions as the origin of planetary systems. Planets lacking the stable climatic and compositional regime characteristic of Earth might be dominant, even though there would be no chance of their being observed from within their own system because of the absence of indigenous life.

Therefore, progress in understanding the formation of planetary systems necessitates acquiring an adequate random sample of other systems. A start in that direction is already occurring on a rather small scale, using modest Earth-based facilities. Progress on this central problem will require larger Earth-based and eventually space-based observational facilities.

Key Questions

Key questions with respect to planetary systems include (in no particular order) the following:

- How did nebular dust grains agglomerate into planetesimals of about 1-km diameter?
- How and when did the stage of growth of planetesimals into embryos end and the final stage of growth of embryos into planets begin? What fraction of the mass of the system remained as small planetesimals at that time?
- Could embryos in the regions of Jupiter and Saturn grow large enough during the low-velocity stage to permit rapid accretion (in about 10^6 to 10^7 years) of their hydrogen- and helium-rich envelopes?
- Did Jupiter prevent the development of full-size embryos in the asteroid belt? Alternatively, were embryos actually formed and subsequently removed by mutual perturbations into dynamically resonant regions? What are the implications of these alternatives for the record of early solar system events preserved in meteorites of asteroidal origin?
- How did the cores of Neptune and Uranus grow, despite the prior formation of Jupiter and Saturn and the consequent development of dynamically unstable regions in the outer solar system?
- When and how was the residual nebular gas removed from the system? Did this occur all at once, or was it dependent on heliocentric distance?
- How did the satellite systems of the outer planets form? To what extent was their formation analogous to that of the solar system itself?
- How did the process of giant impacts operate? Can it actually explain the events (e.g., lunar formation) attributed to it?
- Can planetary systems be detected about other stars? If so, can their attributes be determined?

Primitive Bodies

Comets, asteroids, meteorites, and interplanetary dust—the so-called primitive materials—offer important constraints to possible early histories of our planetary system. Detailed measurements of composition (elemental, molecular, isotopic, and mineralogic) provide a rich database for deducing the physical and chemical environments in which these primitive materials were formed and aggregated and the evolution of those environments. In particular, certain meteorites have apparently undergone minimal chemical fractionation so that their compositions are believed to reflect that of the protoplanetary nebula. Analysis of such meteorites therefore forms much of the basis for compilation of "solar" abundances.

Information from comets pertains to interstellar environments and conditions in the outer solar system where comets originated. Information from asteroids pertains to the transition zone between the terrestrial and jovian planets where asteroids grew and many still reside. Both types of bodies are remnant planetesimals, in most cases having undergone comparatively little modification during the 4.5 billion years since formation. These are the best available examples of the entities that were the building blocks of the present planets. In many cases they are probably identical to such constructional materials and, as such, contain, in the case of comets and volatile-rich asteroids, the late-accreting "veneer" that, at least in part, supplied volatile elements to the terrestrial planets.

The only primitive materials available for study in terrestrial laboratories are meteorites, interplanetary dust grains, and the interstellar grains preserved within them. These materials are principally derived in uncertain proportions from asteroids and comets, objects that (while the subject of extensive ground-based observations) have only recently begun to be studied by spacecraft. The Ulysses spacecraft has also detected small dust grains ejected from Jupiter and other such grains streaming into the solar system from interstellar space.

Comets

Comets are small, dark bodies composed of a mixture of refractory particles, CHON (containing carbon, hydrogen, oxygen, and nitrogen) grains, and ices (predominantly water).[5] For comets to have grown to planetesimal size in a reasonable amount of time, the density of the protoplanetary medium must have been many orders of magnitude higher than that found in molecular clouds. Thus growth must have taken place within the solar nebula (in the region of the outer planets and somewhat beyond) or in some other region of high dust concentration. It appears likely that the present source of the short-period "Jupiter family" of comets is the Kuiper Belt located some 50 AU from the Sun. The long-period comets, with nearly parabolic orbits, come from the Oort Cloud at about 5×10^4 AU. The latter must have been placed in Oort Cloud orbits by planetary scattering. Jupiter and Saturn are not the favored scatterers because their large masses would eject most comets from the solar system entirely. Also, their positions in the solar nebula would preclude incorporation of the more volatile gases into comets. Thus, the primary scatterers are likely to be Uranus and Neptune. Galactic tides permit the perihelia of these comets to escape from Uranus- and Neptune-crossing orbits. Perturbations by passing stars and molecular clouds can then cause the Oort Cloud to extend beyond 5×10^4 AU. Interactions with molecular clouds, however, truncate the Oort Cloud at about 10^5 AU. These gravitational perturbations can also cause comets within 5×10^4 AU to diffuse back into the inner portions of the solar system, where solar heating gives comets their familiar comae and tails.

The mass of the Oort Cloud is speculative; it may contain 10^{11} comets with individual masses greater than about 10^{12} kg. The short-period comets from the Kuiper Belt are the principal sources of the shower and sporadic meteors observed on Earth. In their dormant states, they probably represent a significant fraction of the population of Earth-approaching "asteroids" and Jupiter-crossing objects of asteroidal appearance.

Comets are most notable when they approach the Sun and develop a gaseous coma (Figure 3.4). The characteristic cometary coma obscures the nucleus as seen from Earth. Accordingly, most of our knowledge of the properties of comets has resulted from deductions about plausible physical and chemical processes based on measurements of the species populating the comae. The Halley campaign during the 1986 apparition has confirmed and augmented some of these theories, but fundamental properties (e.g., bulk density and rotation state) of even that comet's nucleus remain elusive.

Ground-based observations, coupled with results from the Halley flybys, have indicated the molecular makeup of cometary volatiles: water ice constitutes about 80% of the ices, while the other molecules are probably trapped in the water ice. The other 20% of the frozen material is composed of molecules such as CO, CO_2, CH_4, and NH_3 that are common in the outer solar system, as well as more complex molecules such as H_2CO, HCN, C_2H_2, and maybe even long-chain hydrocarbons that point to chemical complexities in the early solar

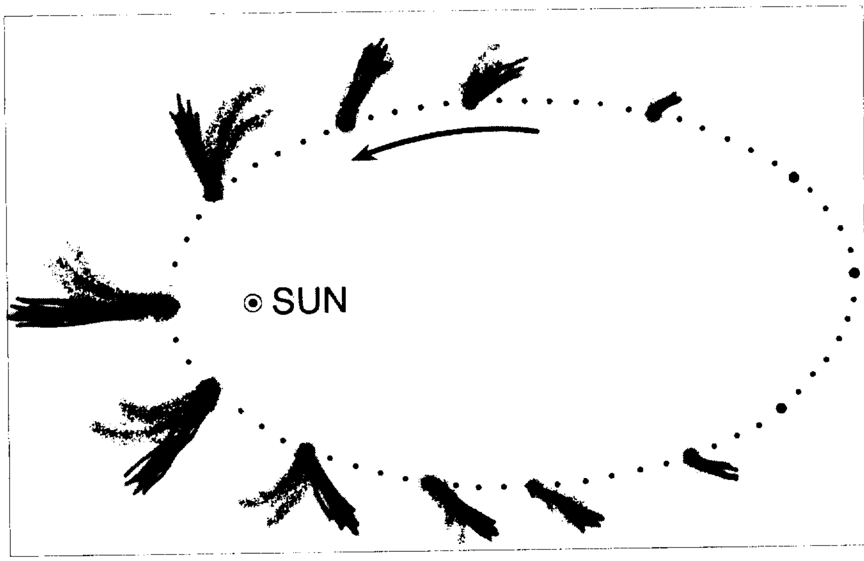


FIGURE 3.4 A cometary orbit. The orbit of a typical comet that has been perturbed into the inner solar system is highly elliptical or nearly parabolic. As the comet approaches the Sun, some of the ices sublime to form a coma. Through photochemical reactions, some of the gases are ionized. The ionized gases interact with the charged solar wind to form a gas tail pointing away from the Sun. Outflowing solids trail behind the comet in the orbit, forming a dust tail; the most visible particles are pushed away from the Sun by radiation pressure and hence drift further back.

nebula. However, the study of the abundances of all of the ices is quite immature, and our knowledge of the comet-to-comet variations remains poor. Some of the trace species, such as CO, seem to vary considerably between comets, and it is not known if this perceived variation is a consequence of different formation or evolution.

Recent studies of the Infrared Astronomical Satellite data set indicate that comets may contain more dust (by mass) than volatiles. Accordingly, a new paradigm of comets as icy dustballs may replace the older model of comets as dirty snowballs. The properties of the dust are mostly unknown, although infrared observations of the silicate features at 10 microns may point to a strong link with the interstellar medium and, by inference, with the presolar nebula material. Spacecraft measurements of cometary dust coupled with laboratory investigations of interplanetary dust particles show that these materials contain siliceous and organic components. These components are intimately mixed on all size scales. These materials are fine-grained (submicron) and highly unequilibrated. Comparisons of the 10-micron silicate emission features in comets and collected dust indicate that cometary silicates contain both amorphous and crystalline components. The combined elemental composition of dust and gas leads to the conclusion that comets are the least altered bodies remaining from the early solar nebula.

The rotation periods of fewer than 10 comets are known; so few have been measured because the presence of a relatively bright coma makes most photometric observations difficult to interpret. Moreover, some comets, such as Halley, display complicated light curves that cannot be easily inverted. Nevertheless, significant brightness variations imply that cometary nuclei must be quite irregularly shaped. Global cometary albedos are extremely low, indicating that much of the nucleus is covered by black material, despite the fact that ices are abundant. Indeed, the spacecraft missions to Halley showed that less than 10% of this comet's surface was active, and that the remainder was apparently coated with an extremely dark lag deposit.

Comet Halley is the only comet whose size and gross morphology are known with any precision. Halley is an elongated, potato-shaped object with dimensions of roughly $16 \times 8 \times 8$ km. The sizes of some other cometary nuclei are inferred from ground-based magnitudes determined when the coma activity was thought to be minimal, combined with the assumption that all comets have an albedo of about 5%. According to this method, most comets have sizes of the order of 1 to a few kilometers. In contrast, Chiron, an unusual comet-like object that moves on an elliptical orbit between Saturn and Uranus, has a radiometrically determined radius of 100 to 150 km, distinct from the inferred small sizes of most measured comets.

Neither the mass nor the density of any comet has been determined. The spacecraft that visited Halley, Giacobini-Zinner, and Grigg-Skjellerup did not pass close enough to these comets to have the spacecraft orbits gravitationally perturbed by the cometary masses. Studies of the outgassing behavior of comet

Halley have led to estimates of its density, but systematic uncertainties preclude any meaningful constraints.

Many comets seem to display nonperiodic changes in their brightness and appearance. Sometimes this is correlated with an increased outgassing. Currently there is very little understanding of this unpredictable activity, and one cannot even state whether it is a common attribute of all comets. Indeed, the nature of the erratic behavior differs from comet to comet, and it is not known whether the observed different types of activity are related phenomena or not. The activity and duration of the cometary coma may depend on the number of approaches that the comet has made to the Sun and, specifically, whether the observations were made during a particular comet's first perihelion passage. Comets have been seen to fragment on close passages by the Sun and Jupiter, and occasionally to split in interplanetary space, with no proximate cause.

Asteroids

Asteroids are small, rocky, and metallic bodies scattered across the region between 2 and 5 AU from the Sun.[6] In some locales, asteroids such as Jupiter's Trojans are trapped by planetary perturbations, whereas other zones, such as the Kirkwood gaps, are depleted by resonant perturbations that can lead to chaotic dynamics. Over 5000 minor planets have permanent designations indicating that their orbits are well determined. Many of these are the brightest, largest bodies, whose population statistics are thought to be complete. However, the fainter asteroids are only partially sampled, such that full knowledge of the size distribution of small bodies is quite uncertain. The known sample has sizes ranging from Ceres, with a diameter near 1000 km, to some of the Earth-approaching asteroids, with sizes of ~10 meters. Ceres is a more or less spherical body and could represent an original undifferentiated body. Most of the smaller asteroids are probably collisional fragments of highly irregular shape that are remnants of larger bodies. Recent radar studies of two Earth-approaching asteroids have shown these bodies to have highly contorted shapes, almost like dumbbells.

Our knowledge of asteroids comes primarily from ground-based astronomical observations and from laboratory studies of meteorites. These two techniques offer very different approaches to understanding asteroids and can provide separate constraints on solar system formation. Unfortunately, the relationship of specific meteorites to the parent bodies is very problematic; accordingly, the origins and subsequent histories of meteorites are very uncertain. The astronomical observations of asteroids chiefly measure the brightness variations and spectral properties of unresolved images. These observations yield information about sizes, shapes, spins, and surface texture and mineralogy, but little about cratering or true bulk composition. Spatially resolved information has been obtained for a few asteroids from radar and perhaps interferometry. As yet, only two asteroids, 951 Gaspra and 243 Ida, have been imaged by a spacecraft; surprisingly, they both display a softened regolith, grooves, and different populations of craters, with Ida having larger-size craters.

On the basis of astronomical measurements, asteroids have been grouped in approximately a dozen taxonomic types, presumably associated with mineralogical composition. The predominant classes are several low-albedo types (believed to be of hydrous and anhydrous carbonaceous composition) and silicate-metal mixtures. In addition, there are some rare types. These groupings are determined from reflectance spectroscopy and multicolor photometry and distinguish bodies only along the broadest categories. Albedo information is added to further differentiate groups. Since meteorites are believed to be fragments of asteroids, there has been an attempt to link the asteroids that are studied remotely with the meteorites that are scrutinized in the laboratory. Such comparisons indicate that there are some asteroid types for which no meteorite analogs are available today and some meteorite classes for which no asteroid relations are known.

Many asteroids are members of families (clusters of asteroids that have similar orbital properties; these objects frequently fall into similar taxonomic types). Such families are believed to result from collisional disruption of larger precursor bodies. The membership of all but the major families has often been a source of controversy, with little certain evidence that the different family members are indeed related. Spectral confirmation of such families is rare because of the general similarities of many asteroid spectra. However, there have been cases where spectral confirmation of the dynamical family does exist. Recently, objects similar to Vesta (a large asteroid of a very unusual type) have been discovered much further from the Sun than current cratering-mechanical theories would predict.

Asteroids tend to become darker and increasingly more "primitive" at greater heliocentric distances. These trends have been interpreted as being due to compositional variation, with stony and metallic bodies lying nearer the Sun while bodies with a carbonaceous spectral signature reside further from the Sun (Figure 3.5). This compositional segregation could reflect the temperatures in the solar nebula at which various materials condensed or differences in differentiation history as a function of heliocentric distance.

As observations improve and more objects are discovered, the distinctions between comets and asteroids are increasingly blurred. A few asteroids have been noticed to show "cometary" emissions; a number of dormant or dead comets are undoubtedly present in planet-crossing "asteroidal" orbits; and an increasing number of enigmatic objects that defy classification into the traditional groups are being found in the outer solar system and on elongated orbits that loop into the terrestrial-planet region.

The near-Earth asteroids represent a special group. Fragmentation of these objects, most of which have aphelia in the main asteroid belt, must contribute to the meteorite population. With respect to the information they can provide, the

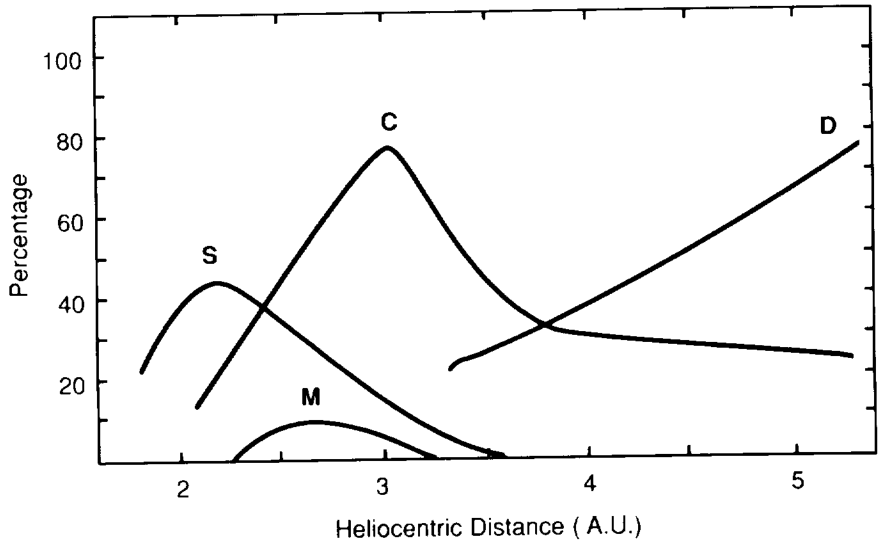


FIGURE 3.5 The distribution of asteroid taxonomic type with heliocentric distance. The different taxonomic types are not uniformly distributed in the asteroid belt. Instead, bodies that are believed to be more rocky (S-type) or metallic (M-type) occupy the inner belt, while the more carbonaceous (C-type) and primitive (D-type) bodies occupy the outer region of the belt.

principal disadvantage of these bodies is that, like meteorites (discussed below), they have lost most of the information regarding their locations in the solar system prior to their relatively recent injections into Earth-approaching orbits. The additional possibility that many of these bodies may be inactive comet nuclei rather than asteroidal fragments has both negative and positive aspects. Making such an identification would be of substantial interest in its own right. On the other hand, the inability to say whether a body under investigation originated in the asteroid belt or the cometary source regions in the outermost solar system would limit the importance of such bodies for questions of origin.

As is the case for all objects in the solar system, we are at an early stage in an understanding of the processes by which asteroids grew from small planetesimals into objects as large as Ceres. For asteroids, an additional question concerns why full-scale planets did not form in the asteroid belt. Discussions of these questions have generally made the reasonable assumption that the total mass density of solid material in the asteroid belt was comparable to that in the adjacent terrestrial and gas-giant planet regions and was reduced a thousandfold to its current value by external causes, probably as a result of the formation of the giant planets.

Current models imply that Moon- to Mercury-size bodies, commonly termed "planetary embryos," formed in only about 10^5 years at 1 AU as a result of a process of runaway growth. Similar calculations for the growth of bodies in the asteroid belt indicate that Ceres-size objects would also have formed in about 10^5 years, but even with a rather generous allocation of solid surface densities at 5 AU, only Mercury-size "proto-Jupiters" would have formed on that time scale; it seems unlikely that such a small body could have quenched the runaway growth of much larger objects in the asteroid belt. This discrepancy presents an opportunity for theorists to show that these calculations are seriously incorrect, or to devise another quantitative theory that prevents runaway growth in the asteroid belt but is also consistent with other observational data obtained from meteorites, the asteroids themselves, and the terrestrial planets.

Alternatively, it is possible that a fairly large number of Mercury- to Mars-size objects did indeed form in the asteroidal region on a 10^6-year time scale, well before the full growth of Jupiter and Saturn on a 10^7-year time scale. Quantitative calculations then show that large bodies in the asteroid belt would have been removed by the same processes that dislodge meteorites and Earth-approaching asteroids from the present solar system: injection into giant-planet resonances (by mutual perturbations rather than collisions), and/or close approach to Jupiter, leading to ejection from the solar system. In about half of the cases studied, these processes completely clear large bodies from the asteroid belt. According to such a model, the present asteroids are a mixture of residual planetesimals that failed to accrete into large bodies and surface chips or spalls from the larger bodies. An interesting feature of this model is that it provides a natural explanation for the observed 5-km/s average relative velocities of the present asteroids.

These alternative models certainly lead to different observational consequences regarding the meteoritic record, the compositional distribution and collisional history of the present asteroid belt, and the time scale for major impacts in the terrestrial planet region. Little attention has been directed so far to identifying those differences, but such studies should contribute to the planning of future asteroid missions.

Meteorites and Interplanetary Dust Particles

Meteorites probably come predominantly from the inner asteroid belt and from near-Earth asteroids, which themselves are thought to be derived from both comets and main-belt asteroids. Interplanetary dust particles are distributed throughout the solar system and form the zodiacal dust cloud. Such grains originate from both comets and a wider distribution of asteroids, including asteroid families.

Since meteorites and interplanetary dust particles are analyzed in terrestrial laboratories after their collection, these bodies have been investigated at a level of detail far beyond asteroids and comets. In addition to bulk mineralogy and physical properties, trace elements and isotopic abundances have been studied. From these measurements one can derive chronologies plus information on environmental conditions (pressures, temperatures, oxidation states, magnetic fields, and so on) and processes (condensation, evaporation, mixing among nebular regions, production of organic matter, exposure to the solar wind, and others) that constrain solar formation models. However, because meteorites and dust grains cannot yet be directly linked to their original sources, and because the origin of these sources themselves is not well understood, this detailed information is not yet as informative as it might be concerning the solar nebula.[7]

The interplanetary dust grains that are captured by Earth's upper atmosphere fall into two distinct classes as defined by their elemental, chemical, mineralogical, and isotopic properties: the hydrated particles and the anhydrous particles. The hydrated particles are nonporous with smooth exteriors and contain abundant hydrated silicates along with carbonates and magnetite. The anhydrous dust particles, for which there are no meteorite analogs, are composed of anhydrous minerals and glass and are porous, with little compaction. The bulk composition of most interplanetary dust grains is similar to that of carbonaceous chondrite meteorites, but the presence of microstructure and absence of postaccretional processing suggest that interplanetary dust grains may be even more pristine than chondrites.

Meteorites are usually cataloged according to one of several distinct classes. This diversity implies a variety of formation environments and subsequent alteration processes. The recent discovery of individual, preserved interstellar grains in both meteorites and dust, as identified by isotopic anomalies, provides a direct link between the interstellar medium and our solar system. Many of these anomalies point to specific extrasolar nucleosynthetic sites. The processes that subsequently modified these materials include those that took place in the nebula (e.g., chondrule formation, chemical fractionation, and grain formation) and those that occurred in the parent bodies (heating, differentiation, aqueous alteration, impacts, and so on).

Key Questions

Key questions with respect to primitive bodies include (in no particular order) the following:

- How did the orbits of planetesimals in the outer solar system evolve to form the present-day comet reservoirs, the Kuiper Belt and the Oort Cloud?
- How did the asteroids form, and on what time scale? Have much larger bodies ever existed in the asteroid belt? To what extent do the present positions of the asteroids reflect the locations at which these bodies were formed?
- What are the relationships between the various primitive bodies? What

regions do the meteorites and interplanetary dust particles sample, and can we identify the parents for these objects?

- How much modification have asteroids and comets undergone since they were first formed? How well can such materials provide boundary conditions on early solar system environments, including pressure, temperature, chemical and isotopic mixing, time scales, composition, and so on? How can the detailed record of nebular events preserved in meteorites and primitive bodies be more fully utilized?
- What is the nature of the heat source(s) responsible for differentiating a fraction of the asteroids and causing the metamorphism observed in chondrites? Was this thermal episode due to radionuclide decay, affecting primitive materials throughout the solar nebula, or to processes such as collisional or induction heating, which could have a heliocentric dependence?
- What are the observational biases that limit our ability to link the current state of objects with their initial state?
- What relative role have comets and asteroids played during their bombardment of planetary surfaces throughout solar system history? To what extent have they contributed to the budget of volatiles and organics on the terrestrial planets?
- How important are comets and asteroids for the presence of water on the terrestrial planets and the origin of life, or conversely the frustration of the origin of life?
- What are the basic properties of comets and asteroids such as bulk densities and rotation state? Are any bodies rubble piles?

Life

Life is fundamentally an accumulation of organic chemical processes of sufficient complexity to be mutating and self-replicating.[8] Studies that bear on the origin of life are necessarily broad, incorporating a spectrum of disciplines from astronomy to paleobiology. The underlying goal is to understand the origin and evolution of living systems.

It is commonly presumed that Earth is the only planet in the solar system on which life arose. If this is the case, why is it so? Terrestrial organisms occupy a wide range of environments, some that possibly occur on other bodies in the solar system. Perhaps life, so far undetected, occurs elsewhere in the solar system. Or, perhaps life did arise on other bodies and then perished, or the accumulation of organic complexity did not reach the level required for life. In any case, some stages of organic complexity that led to life might still be available for analysis. It is also important to identify and understand the environments in which life failed to emerge. In short, knowledge of the processes that produce organic matter, wherever it occurs in the solar system, is central to our understanding of the chemical evolution of life.

At present little is known about prebiotic chemistry. The building blocks of cells are simple organic compounds, readily created in the laboratory from simpler compounds that are abundant in the cosmos. For instance, mixtures of methane, ammonia, and water exposed to electric discharge or other energy sources yield the amino acids of proteins and the bases of nucleic acids. However, there is a vast gulf in our knowledge of the chemical steps that must have occurred between the formation of simple organic compounds and the rise of complexity that bred life. What is clear from astronomical studies is that organic complexity is ubiquitous, not only in association with major bodies, but also in interstellar space. Some major bodies, conspicuously Titan, are rich in hydrocarbons. Organic materials also are thought to be significant components of comets and asteroids (and probably Triton and Pluto). Some carbonaceous meteorites have been found to contain amino acids and other life-related organic compounds, as well as organic polymers that are little understood because of their complexity. Organic compounds also are formed and undergo transformations toward complexity in circumstellar and interstellar space, in molecular clouds, and in association with granules such as presolar grains and interplanetary dust particles. Compounds detected astronomically include aldehydes, ketones, hydrocarbons, and polycyclic aromatic hydrocarbons. Such substances and the mechanisms that form them likely contributed to the pool of organic chemistry that led, on Earth, to life.

Prebiotic and early biotic evolution requires the existence of a physical environment in which temperatures are neither too high to threaten the chemical stability of complex organic molecules, nor so low that chemical reaction rates are extremely sluggish. Furthermore, conditions must be suitable to permit both solution and surface chemistry. These requirements suggest that planets with liquid water on their surfaces (i.e., planets similar to Earth) are prime candidates for sites of the origin of life. This is true not only in our solar system, but also throughout the galaxy and the rest of the universe. One objective of studies into planetary origins is to understand the frequency with which Earth-like worlds occur in other planetary systems. Such studies must operate in an iterative manner, making full use of information derived from theories on planetary origins, ground- and space-based astronomical observations, space missions, and laboratory studies of extraterrestrial material. Serious work of this kind is only in its infancy. Nevertheless, interesting progress is being made. Global climate models are, for example, being used to identify the position of "habitable zones" around other stars as a function of their spectral type. Similarly, theories on planetary formation are being used to explore the circumstances in which planets capable of retaining surface water are likely to form within these habitable zones.

The actual nature of the environment needed for life to emerge is currently unknown, but the requirement of liquid water is highly plausible. Further study of Mars, with its record of abundant liquid water early in its history, is of major importance in this regard. Whether or not evidence is found for extinct, or even extant, organisms, the exobiological exploration of Mars will lead to a more constrained definition of the planetary conditions that constitute a "window of opportunity" for the emergence of life. The ocean that probably underlies the icy crust of the jovian moon Europa is another important, albeit not currently accessible, environment to study in this regard.

Life probably originated on Earth as soon after the planet formed as conditions permitted. The earliest history of life therefore lies in the chemical processes undergone by the biologically dominant elements (hydrogen, carbon, oxygen, nitrogen, sulfur, and phosphorus) during the formation of the solar system and the accretion of the planets. These processes sparked the origin of the first cells. The later history of life is seen in the course of evolution that led to modern biological complexity and the molding of the terrestrial biosphere. The final strategy document from the former Committee on Planetary Biology and Chemical Evolution recommends a comprehensive collection of space- and Earth-based studies that is likely to resolve major questions regarding the origin of life.[9]

Much of what we know about the origin of life stems from studies of either life itself or its remnants. There is convincing evidence in the form of microfossils and stromatolites that life existed on Earth 3.5 billion years ago. More tenuous, isotopic data suggest the presence of life as early as 3.8 billion years ago. This latter date is, however, only a few hundred million years after the end of a period of similar duration during which the coalescing Earth was subject to sterilizing bombardment. Since Earth would have been in a phase of rapid cooling at this time, it is likely that life arose at higher temperatures than those currently experienced on Earth's surface.

Molecular evolution studies, based on comparisons of molecular sequences from extant organisms, are consistent with this inference. They indicate that the most "primitive" known organisms are those that thrive at temperatures greater than 373 K and utilize geochemical compounds such as H_2, CO, and H_2S for growth. These types of organisms are found in modern-day environments such as submarine hydrothermal vents, the type of environment that may have been dominant on the early Earth.

Although the detailed properties of the earliest organisms are unknown, some of their fundamental aspects can be inferred. Comparative molecular data show that all extant life forms are related to one another. Thus, there must have been a common ancestor of all life on this planet. The last common ancestor was already sophisticated and would have had the properties common to all modern organisms. These characteristics include genetic information encoded in DNA molecules, a well-developed translation apparatus, and the use of adenosine triphosphate (ATP) as energy currency.

Before that last common ancestor there was the postulated "progenote." While possessing a rudimentary biochemistry, this nearly undefinable and not necessarily cellular entity had a highly error-prone replication mechanism and was, therefore, rapidly evolving. With the origin of replication, natural selection would have rapidly advanced life toward the character of modern cells.

Spaceflight offers a window on the prebiotic environment, a part of life's history that is no longer available on Earth. Cometary nuclei, primitive asteroids, and planetary and satellite surfaces provide sites to sample the evolution of the chemical complexities of the biogenic compounds throughout the course of the formation of the solar system. Much of the information necessary for progress in understanding the prebiotic sequence of events that ultimately produced life is also needed by other disciplines. However, some of the methods required for prebiological considerations are specialized but particularly important for the discipline. These include, for example, the capability to analyze high-molecular-weight carbon-containing compounds. Other special requirements include targets for study. Some places, Titan for instance, offer rich organic chemistry and so are of high priority. Other targets, notably Mars (and possibly Europa), have special importance for studies of the origin of life because conditions have occurred there that resemble terrestrial environments, whereas cometary nuclei can probably provide our best sample of prebiotic material.

Key Questions

Key questions with respect to life include (in no particular order):

- What was the history of physical and chemical transformations undergone by the biologically dominant elements during the formation of the solar nebula and the planets?
- How and when were these elements added to the surface regions of Earth and other planets? Were they primarily included with the planetesimals that accumulated to form the planets, or were they subsequently added as "late veneers" from more volatile-rich regions of the solar system?
- How did prebiotic molecules form in the physical and chemical environment of the early Earth, and how did these molecules interact to engender protobiological functions?
- How did protobiologic systems evolve into replicating systems and into cellular organisms?
- Did Mars ever accumulate a reservoir of prebiotic organic compounds, and does any trace of such material remain on Mars today? Is there any evidence that organic matter underwent prebiotic chemical evolution on Mars?
- Did life emerge on Mars and, if so, did it leave any record of extinct life forms? Is there any evidence for life on Mars today?
- What are the processes responsible for organic chemical evolution in the outer solar system, including the atmospheres of the outer planets and Titan?
- What is the frequency of occurrence in other planetary systems of habitats suitable for life?

OBJECTIVES

Objectives to be addressed in the study of origins include (in no particular order) those discussed below.

Protoplanetary Disks

- Use theoretical modeling to develop a detailed understanding of the formation of stellar and planetary systems, starting from the formation of dense molecular cloud cores. Theoretical models form the conceptual framework on which our understanding of protoplanetary disks is developed and tested against observations. However, there is no detailed theoretical model that extends from the earliest phases of the collapse of a dense molecular cloud core through to the removal of the last vestiges of gas and dust from the regions of the newly formed planets. Achieving this basic theoretical and conceptual understanding must rank as a foremost objective if we are to understand the origin of the solar system.
- Use observations of nearby star-forming regions (especially the properties of protoplanetary disks) to guide and constrain our understanding of protostellar formation. The final proof of the validity of the theoretical model discussed above can come only from systematic observations of systems that are likely analogs to the solar nebula—the protoplanetary disks now being detected around nearby young stars. In principle, these observations should be able to find definitive evidence for protostellar collapse, distinguish between the formation of single and binary protostars, delineate the phasing of stellar outflows and their effects on the disk, decide what mechanism predominantly controls the transport of mass and angular momentum in the disk, and define the physical and chemical characteristics of these disks in the primary planet-forming regions (especially inside ~10 AU).
- Employ observations of primitive solar system objects to define conditions and processes during the evolution of the solar nebula. Within limitations stemming from uncertainties in formation locations and possible alteration of the primordial record, such studies can yield information about time scales, thermal evolution, chemical fractionations, radial mixing, magnetic fields, and other properties of the protosolar system.

Planetary Systems

- Develop an internally consistent, quantitative theory of the formation of our entire planetary system that contains sufficient detail to permit comparison with as much observational evidence as possible, including the meteoritic record. A theoretical understanding of the entire process of planetary accumulation from micron-size dust grains to the final planets does not currently exist. While segments of this global theory have by now been fairly well studied (e.g., the final accumulation of the terrestrial planets), until a complete theory is developed it will not be known if these segments can be fit together into a cohesive whole (e.g., did the initial conditions assumed for the final accumulation of Earth ever actually occur?). The very process of assembling these segments into a smooth whole will undoubtedly cause significant reworking of many (if not all) of the scenarios for the various stages of planetary formation.

- Detect and determine the orbital properties of planetary systems in orbit around enough nearby stars to yield a statistically significant estimate of the frequency of planetary systems. Such a search naturally would first attempt to locate Jupiter-mass planets, would then proceed to Uranus-mass planets, and ultimately would look for evidence of Earth-mass bodies. All thought about the origin of our planetary system is limited by the single example available to study, which by the very presence of humans may not be representative of other planetary systems in our galaxy. Only after such a search for extrasolar systems is completed will the likelihood of formation of a system similar to the solar system be truly understood.
- Once extrasolar planets are detected, use bolometric luminosity measurements and spectroscopy to determine atmospheric temperatures and compositions, respectively.

Primitive Bodies

- Define the population of carbonaceous materials in cometary nuclei. The elemental, molecular, isotopic, and mineralogic compositions of a variety of samples of primitive bodies must be measured. Some of these measurements may be accomplished by augmented collection and further investigations of meteorites and interplanetary dust particles. Others require in situ studies of asteroids and comets and/or return of samples. This information should be compared with similar elemental abundances obtained from meteorites and other sources.
- Identify the sources of the extraterrestrial materials that are received on Earth.
- Seek correlations between the properties of asteroids and comets (such as compositional types, sizes, rotation states, heliocentric distance, family membership, and so on). Laboratory studies must also be advanced, in particular those of meteoritic samples divided into classes on the basis of mineralogy, elemental fractionation, isotopic composition, and other such parameters. It is very important to improve knowledge about which particular bodies, or classes of bodies, are the sources of the diverse samples available for detailed laboratory analysis.
- Determine the internal structure, geophysical characteristics, and surface geology (including bulk density, rotation states, internal heterogeneity, crater distributions, topography, and general tomography) of comets and asteroids. Such studies may be accomplished through spacecraft-borne radar studies, spec-

troscopic investigations, and geodetic measurements, as well as by the application of more sophisticated seismic monitoring. Specific descriptions of a few particular targets should be augmented with a general characterization of the size distribution and orbital properties of the whole complement of small bodies.

- Understand the range of activity of comets, including the causes of its onset and its evolution. This requires that activity be studied for representative comets from aphelion through perihelion. It is most important that observations be made of the nucleus and the nucleus-coma interface, and that the constituents of the nucleus be analyzed through ground-based observations, then in situ, and eventually through sample return.
- Ascertain the early thermal evolution and processes of geochemical differentiation of small bodies by assessing the properties of a differentiated asteroid or fragments of a differentiated precursor. Such goals can be addressed by detailed geological and compositional studies of the heterogeneous parts of such a body.

Life

- Define the inventory of organic compounds in the cores of molecular clouds and improve our understanding of the prebiotic organic chemistry that took place in the solar nebula. Radio observations continue to reveal that novel organic compounds occur in these environments. Such compounds would have contributed to the accumulation of organic complexity on the primitive Earth and other bodies.
- Improve knowledge of the processes that led to the emergence of life on Earth, and determine the extent to which prebiotic and/or protobiological evolution has progressed on other solar system objects, specifically Mars and Titan. Beyond generalities based on modern cells, little is known about the chemical transformations that resulted in self-replicating molecules. Even the nature of the environment in which life arose is not known. Analysis of organic compounds on bodies other than Earth may reveal prebiotic chemicals similar to those on Earth before life appeared and thus yield insight into the origin of life.

Measurement Objectives

Recent Space Studies Board and NASA reports have outlined detailed measurement objectives that pertain to primitive bodies and the origins of both the solar system and life.[10–12] The objectives outlined earlier in this section are amenable to research at different levels of detail. For the primitive bodies, detailed compositional information, both elemental and isotopic, should be obtained. The measurements that are desired, and the necessary precision, are outlined in COMPLEX's *Strategy for the Exploration of Primitive Solar-System*

Bodies.[13] A strategy for the search for extrasolar planets has been outlined as part of the 1992 report of NASA's Toward Other Planetary Systems Science Working Group.[14] The Committe on Planetary Biology and Chemical Evolution has derived a strategy for the study of the origin of life, with suggestions about necessary measurements.[15] COMPLEX endorses these suggestions for measurements, including the levels of precision and accuracy needed.

WHAT TO STUDY AND WHERE TO GO

Spacecraft missions, particularly those that returned samples from the Moon, have played a pivotal role in advancing our understanding of the solar system's origin. Of comparable or even greater importance, however, have been laboratory studies of materials from primitive bodies (meteorites and interplanetary dust particles), observations of stars in the process of formation, and theoretical modeling of star- and planet-forming processes. Thus it must be recognized at the outset that interplanetary spacecraft missions constitute only one component of a healthy program for investigating questions about the origin of the solar system. However, it is nevertheless useful to discuss the relationship between missions to specific objects in the solar system and the major questions and objectives described in the previous section.

Comets

From the point of view of studying origins, a principal difficulty is that observations made on any particular object can directly reveal only its present state. It is necessary to use that present state to infer information relevant to the origin of the object. All of the larger bodies of the solar system have evolved significantly since they formed. It has, therefore, long been apparent that missions to the relatively unevolved primitive bodies—the comets and the asteroids—are among those with the greatest potential for providing information concerning questions of origin for a given degree of effort. Of the primitive bodies, comets—because of their small sizes, their distant locations from the Sun, their initial elemental makeup, and their relatively infrequent mutual collisions—are likely to be the least modified.

Ground-based studies of comets will continue to provide valuable information, but substantive progress will require rendezvous missions. Given the rudimentary quality of our understanding of comets, an appropriate approach is to deploy an assembly of sensors of various kinds to examine a cometary nucleus as carefully as possible. Rendezvous missions furnish the prolonged observational time needed to study surface processes as nuclei evolve during changes of heliocentric distances.

Detailed planning has been accomplished for a comprehensive comet mission, the Comet Rendezvous Asteroid Flyby, which was canceled because of budgetary priorities, rather than for scientific reasons. Savings from this baseline mission could be achieved by emphasizing the principal motivation for such a comet rendezvous—obtaining data relevant to the solar system's origin; this likely would require that measurements with lower priority be postponed until a future opportunity arises. A comet rendezvous mission focused on origins would contribute appreciably to COMPLEX's previously stated goal of determining the nature of the cometary nucleus by analysis of the composition of its dust and gas constituents.[16,17] COMPLEX continues to assign highest priority to such an investigation.

Of comparable importance would be high-resolution imaging of the morphology and active surface processes of the nucleus, and the determination of global properties such as mean density and rotation. Such observational data, when combined with theoretical modeling, can provide the "ground truth" required to interpret the wealth of data obtained from remote observations of cometary comae and nuclei; it may also help relate these same observations to laboratory studies of interplanetary dust grains. Full exploitation of the unique information contained in comets will require in situ measurements of the cometary surface and interior and ultimately the return to Earth of cometary samples. In order to proceed toward this future goal, the physical properties (e.g., strength and porosity) of the cometary surface must first be accurately ascertained. This will require at least some in situ measurements, probably by a penetrator, even if more elaborate surface experiments must be deferred for financial reasons.

Comets are also believed to have played an important role in supplying volatiles to planetary bodies during the late stages of their accumulation. With regard to the origin of life, analysis of a sample of cometary materials may indicate the degree to which chemical complexity had proceeded and the nature of the prebiotic materials with which Earth was endowed.

Asteroids

Asteroids are distinct from comets in important ways, and meteoritic studies show that in some regards they can be considered as primitive as comets. Full utilization of the information contained in the meteoritic record and the spectral classification of asteroids requires that we be able to directly link specific asteroids with meteorite classes and spectral signatures. Research that explores compositional and physical variation across the asteroid belt is critical to our understanding of thermal conditions and physical processes in the early solar system. The cratering record and morphology of the present-day asteroids offer important constraints on the initial sizes of bodies in the asteroid belt during the formation of the solar system. Properly instrumented rendezvous missions, and ultimately surface sample analyses and/or sample return missions, will be required for achieving an understanding of asteroid origin and evolution.

Terrestrial Planets and the Moon

An important origins-related benefit from the samples returned by the Apollo missions was the progress made in establishing an absolute chronology for a body other than Earth, particularly one with a detailed cratering record extending back to the time when the interplanetary cratering flux was considerably higher than it is at present. The remaining questions about early solar system events at 1 AU can be answered only if this chronology can be carried back to earlier lunar history, with emphasis on avoiding the probable previous bias toward Imbrium-related phenomena. Development of an absolute martian chronology is comparably important to understanding both the early and the later history of that planet. This also is true for Venus and Mercury, but practical considerations exclude such studies of these bodies during the time period under consideration.

Important questions regarding the origin and evolution of solid planets relate to their chemical and isotopic compositions. Insofar as the bulk of a planet's inventory of particular elements is concentrated in a single accessible reservoir (e.g., atmospheric rare gases), measurements of concentrations and isotopic ratios can be relevant to processes in the solar nebula. A particularly important factor is that Mars may provide the best opportunity to obtain observational data concerning chemical evolution processes that were forerunners to life on Earth.

The planet Mercury holds some special interest because of its remarkably high uncompressed density. A chemical and mineralogical characterization of Mercury's surface—when combined with an understanding of surface geology and crustal formation—could contribute significantly to understanding the processes that dominated the inner solar system during its formation.

Outer Planets

Utilizing observational data for the outer planets so as to gain insights into origins necessitates the construction of an appropriate theoretical framework. Development of this framework will require an understanding of the internal dynamics and chemical processes in those active planetary bodies, and an understanding of how those bodies grew as individuals and as members of a system. Within the context of such a theoretical framework, further refined measurements of various isotopic ratios in Jupiter will help clarify aspects of the origin of the solar system. These are discussed in Chapter 4 in the section "Planetary Atmospheres."

Triton and Pluto probably represent planetary embryos formed in the region near Neptune (30 AU and 40 AU, respectively). Better measurements of their inventories of volatiles and organic materials are important for understanding the chemical processes and histories in this region of the solar nebula. Obtaining a census of Kuiper Belt objects, probably by a combination of Earth-based visual and space-based infrared techniques, as well as compositional information, would also be valuable for a determination of early solar system conditions and for comparisons with extended disks of material around other stars.

Extrasolar Planets

Extrasolar planets, once discovered, clearly will be essential for improving our understanding of the origins and prevalence of planetary systems, and implicitly of life itself. For this reason, a search for extrasolar planets commands high priority. A definitive survey for planetary companions of nearby stars could be expected not only to answer the existence question, but also to provide basic physical parameters for these systems: planetary masses, orbital radii, inclinations, and eccentricities. These are the same parameters that theoretical models of planetary accumulation attempt to duplicate for the solar system. It may be possible to use direct detection methods to determine planetary effective temperatures and perhaps to use spectroscopy to determine constituents of extrasolar planetary atmospheres. Estimates of planetary sizes may result from the direct detection of planetary luminosities and measurements of effective temperatures. Similarly, planetary mean densities can perhaps be found from observations of mutual gravitational perturbations. Combining size and density data may answer the initial questions about extrasolar planetary interiors.

Observations of protoplanetary disks yield information almost exclusively about origins. Direct analogs of the solar nebula are thought to exist in relatively nearby star-forming regions, and the ability to probe these protoplanetary disks is steadily improving as telescopes become more powerful across the wavelength spectrum. Examinations of the disks should ultimately confirm or negate otherwise purely theoretical models of planet-forming disks.

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4

How Planets Work

As a result of the last 30 years of solar system exploration, it is now known in a general way whether most of the planets, major satellites, and other principal components of the solar system are red or green, what their surfaces are composed of, how big they are, and so on. We can draw maps of their surfaces, albeit crude ones in many cases, and we can catalog their properties to various levels of detail. But we do not yet understand clearly how the solar system functions. Thus a major goal for the solar system exploration program must be to make sense of the voluminous data obtained so far. This will require additional observations and experiments, as well as theoretical insights. We must ask appropriate questions, fill gaps in our knowledge base, identify key issues, and generally do more than just doggedly measure the same and additional quantities with better and better precision. We must seek to understand, but do it selectively.

The discussion below divides current knowledge about planets into four scientific areas, three of which were studied for Earth by scientists before the space program began:

1. Surfaces and interiors of solid bodies,
2. Planetary atmospheres,
3. Rings, and
4. Magnetospheres.

While this division lays out knowledge of the solar system in a framework with direct comparison to studies of Earth, it is as artificial as the same separation would be for Earth. As ecologists continually remind us today, the nature of an individual planet can be fully appreciated only when the links between its various components are clearly understood.

SURFACES AND INTERIORS OF SOLID BODIES

The surfaces and interiors of most solid bodies of the solar system include the terrestrial planets and the icy and rocky satellites, primarily orbiting the giant planets, as well as differentiated asteroids; primitive asteroids and comets are considered in Chapter 3. The interiors of the giant planets are also included here because of their relationship to the solid planets and satellites in terms of composition and because of their relevance to magnetic field generation.

The space age has transformed the planets and their satellites from astronomical objects to geological entities. They show great diversity in size, composition, and dynamic state, ranging from small, inert rocks, to large, active bodies with atmospheres. Although their activity can be studied as it is now, their solid surfaces preserve, to a greater or lesser extent, the record of events that occurred long ago. Such events include internally generated magmatic and tectonic episodes, erosional and depositional periods, and the formation of impact craters by external projectiles.

The large solid planets have internal structures that are the product of their differentiations, which in turn are influenced by the size, chemical composition, and evolutionary processes of each planet. Such structures include dense cores, silicate mantles, and overlying less dense silicate crusts. In some cases, the cores are responsible for the generation of magnetic fields. Icy satellites are organized somewhat differently: in some cases, rocky interiors are overlain by ice or ice and rock, and possibly crusts of exotic ices.

By characterizing the compositions, internal structures, surface features, and current activities (if present) of planets and satellites, we can infer their internal evolution, their record of external bombardment, and their past climatic changes. Some planets and satellites contain organic molecules and thus information possibly pivotal to understanding the origin of life.

This section's discussion of the surfaces and interiors of solid bodies begins with brief descriptions of current knowledge of the principal planetary bodies of the inner and outer solar system. On the basis of our current understanding, a number of common scientific themes should guide future investigations of these objects. Planetary interiors are discussed in terms of two themes: interior structure and dynamics, and planetary magnetism. Planetary surfaces are discussed in terms of six themes: tectonics, formation and evolution of primary crusts, volcanism and mantle evolution, impact cratering, chronology, and volatiles. Key questions arising from each of these themes are highlighted. Objectives are described in each area that need to be addressed to further studies of planetary surfaces and interiors. Finally, the section "What to Study and Where to Go" identifies the most important studies to be performed and the planetary bodies to be investigated to enhance our understanding of the surfaces and interiors of planetary bodies.

CURRENT KNOWLEDGE

Inner Solar System

The bodies of the inner solar system have been studied through telescopic observations, spacecraft measurements, and a wide variety of laboratory and theoretical research. Much of the detailed knowledge of these objects is derived from missions flown since the 1960s, and the level of this knowledge varies significantly from object to object, depending on the current state of exploration by spacecraft. The following sections briefly summarize the status of exploration of each object; detailed descriptions of the information available about these bodies can be found in many recent books, reports, and reviews.[1]

Mercury

The gross physical properties and rotation state of Mercury have been determined from ground-based telescopic and radar observations. Earth-based high-resolution spectroscopy, thermal emission measurements, radar, and radio studies have yielded information on Mercury's surface layers. The three flybys of the Mariner 10 spacecraft provided 1- to 10-km-resolution images and ultraviolet spectrometric data covering just under half the planet's surface; the spacecraft also measured a magnetic field and traversed a magnetosphere.[2]

Mercury has a heavily bombarded exterior with some volcanic plains. It is inferred that a residual liquid outer portion of the planet's relatively large iron core generates a weak magnetic field, which allows the mercurian magnetosphere to develop. The surface has regional elevation differences, including large scarps that may be a consequence of global contraction associated with cooling and core freezing, but no current internal tectonic or magmatic activity has been identified. The innermost planet is covered with a thick regolith that is probably of intermediate silicate composition and probably extremely poor in iron. An exceedingly tenuous and variable atmosphere contains sodium and potassium. Radar returns suggest the presence of buried icy polar caps, which, due to Mercury's tidally maintained near-zero obliquity, are protected from strong solar insolation.

Venus

The rotation state of Venus and the characteristics of its surface were unknown until Earth-based radar penetrated the planet's visually opaque clouds. Flybys by Mariners 2, 5, and 10 improved the mass determination but observed atmospheric, not surface, characteristics. The Pioneer Venus Orbiter provided nearly global topography and radar imaging, and radio tracking of this spacecraft and others has supplied variable-resolution gravity data. Pioneer Venus's magnetometer placed a strict and low upper limit on any internally generated magnetic field. Surface characteristics of part of the planet were revealed at 1- to 2-km resolution by Earth-based Arecibo and the Soviet Venera 15 and 16 orbital imaging radars, and information on the major-element chemistry of surface materials was provided by Venera and Vega soft landers, which also returned images and surface characteristics for very limited regions of the surface. Magellan's synthetic-aperture radar has provided very high resolution (150-m) maps of surface features over almost the entire globe as well as improved topography (Figure 4.1). The Magellan spacecraft also acquired global high-resolution (200- to 600-km) gravity data.[3]

In Magellan's mapping, Venus shows many impact and volcanic features as well as pervasive tectonic activity, including compression (mountain building) and extension (rifting). The existence of any variant of terrestrial plate tectonics is now in doubt. In contrast with Earth, gravity and topography on Venus are highly correlated, a condition consistent with strong coupling between lithospheric and mantle processes. Elevations show a unimodal distribution, in contrast to Earth's bimodal distribution. The bulk composition of Venus has been estimated indirectly from the similarity in its mean density to that of Earth. Because of Venus's slow rotation rate, the planet's moment of inertia is poorly known, and thus the size and density of the core are not well constrained. Estimates of the thickness of the crust range from about 10 to more than 100 km, and the thickness of the effective elastic lithosphere is currently a matter of debate, with estimated values suggesting a lithosphere much thinner than or similar to Earth's.

The surface rocks on Venus are essentially basaltic in composition; those at the greatest elevations on the planet contain a high dielectric material, such as iron sulfide or magnetite, that renders them markedly radar reflective. The absence of small craters and the presence of unusual impact features have been noted and ascribed to the effect of Venus's dense atmosphere on incoming asteroids and comets. Impact craters are mainly modified by tectonic activity, and crater statistics indicate that a large proportion of the surface appears to have been resurfaced approximately 500 million years ago, although extensive older and younger terrains also exist. Although aeolian features have been observed on Venus, erosion and sedimentation by the wind appear to be minor compared with these processes on Earth and Mars.

Earth

In comparison with the other solid bodies in the solar system, Earth is well studied and understood. Indeed, Earth is the only planetary body for which fairly detailed information, including three-dimensional images of the internal structure, is available from the surface to the center. Most of this knowledge has been derived without input from spacecraft instruments or tracking, but orbital

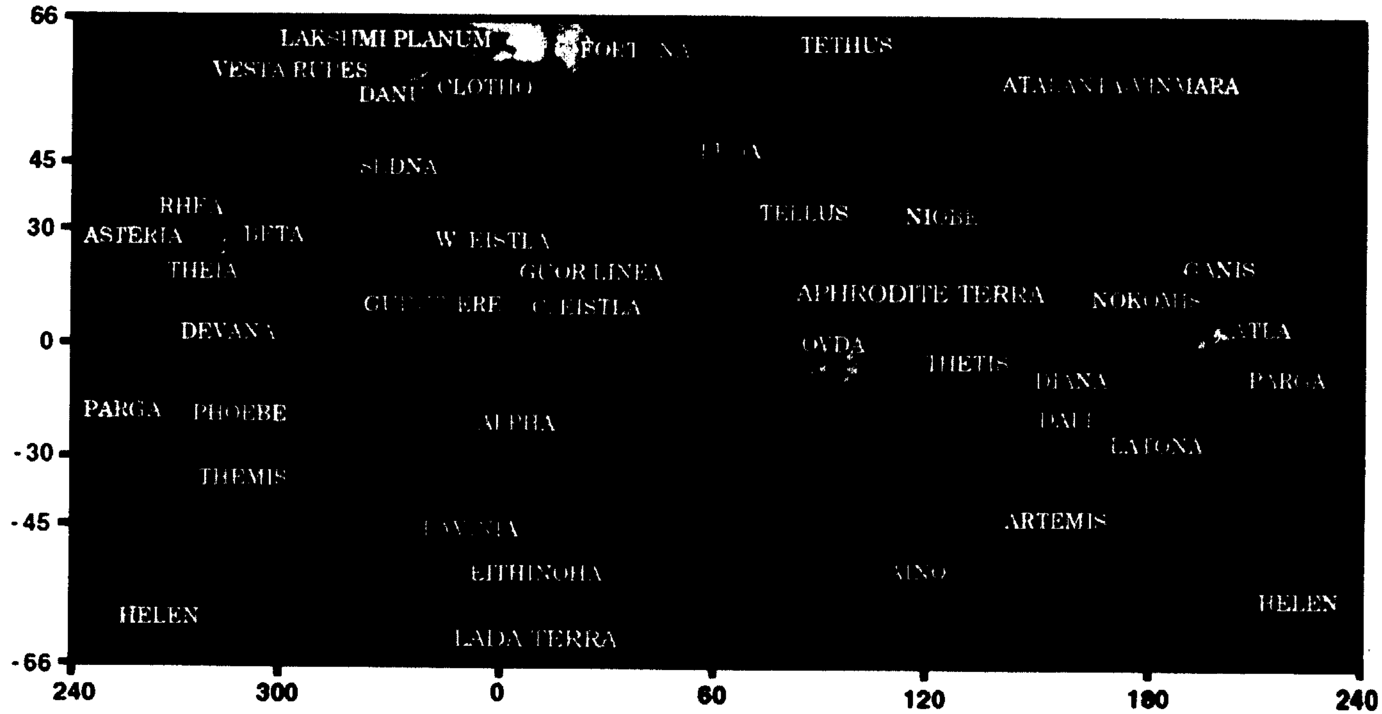

FIGURE 4.1 Topography of Venus, from 66°N to 66°S (and with place names) as determined by the Magellan radar altimeter. Elevations range from greater than 4 km above the mean planetary radius of 6052 km (white) to greater than 2 km below (broad dark gray). The broadly connected light gray regions are plains between 0 and 2 km below the mean. Surface heights on Venus are unimodal, with 80% of the surface lying within 1 km of the mean radius, whereas Earth's topography is distinctly bimodal. Both Earth and Venus display steep features indicative of currently active tectonics. (Courtesy of R.J. Phillips, Washington University.)

data, including gravity and geodesic measurements, have contributed to this knowledge. Unlike other bodies, Earth's near-surface features have been studied at a range of scales from submicroscopic on up, and by means that vary from detailed geological mapping to orbital surveys. Geophysical, geochemical, and isotopic studies of Earth far surpass those of other planets.

Earth is currently the most active of the inner planets. Most of the surface features were formed only in the last 100 million years, although cores of continents date back nearly as far as 4 billion years. Ancient craters such as those observed on many other solid bodies have been preserved only rarely on Earth, and then in a much-degraded state. Observations of the present activity at (and near) the terrestrial surface, and examination of the interior through indirect geophysical methods (principally seismic studies), have led to an understanding of the structure, composition, convection, and melting of the interior. A central metallic core is surrounded by a silicate mantle, which is in turn covered with near-surface crustal materials. Two fundamental types of crust exist: "granitic" continental crust and "basaltic" oceanic crust. Active plate tectonics, driving and driven by mantle convection and intimately associated with magmatic activity (as expressed by mid-ocean ridges and linear volcanic belts) is responsible for much of Earth's morphology. Some fragments of the upper mantle have been brought to the surface by tectonic and magmatic activity. The surface processes, including sediment deposition and surface-atmosphere interactions, are generally well described and well explained as responses to tectonic, volcanic, and hydrospheric activity.

Analysis of the geological record, including laboratory investigations of rock samples, has led to an appreciation of the evolution of Earth, including the evolution of life, over the last 4 billion years. Isotopic studies demonstrate that formation of the core took place 4.56 billion years ago; motion of the fluid outer core gives rise to the current magnetic field, the strongest among those of the inner planets. The geological time scale is comparatively well calibrated, with stratigraphic correlations corresponding to divisions as short as a million years in parts of the Phanerozoic (which extends from 545 million years ago to the present). The geological record demonstrates that vigorous activity, probably in the form of plate tectonics, has characterized all of Earth's history.

Moon

Except for Earth, the Moon was the only planetary body for which surface imaging with a resolution sufficient for geological analysis was available before the space age. Multiple spacecraft missions, including flybys, orbiters, hard and soft landers, sample-return missions, and in situ human exploration, provided considerable scientific information. The available data, taken mainly from 1959 to 1976 (by spacecraft from the United States and the former Soviet Union), include global photography, equatorial chemical mapping, near-side gravity fields, seismometer traces, equatorial topographic profiles, and samples returned by both robots and humans. Spectral mapping was conducted by Clementine and during two recent Galileo flybys, and the Earth-facing side of the Moon continues to be characterized by Earth-based reflectance spectroscopy and radar observations. Earth-based laser ranging has refined the orbital dynamics of the Earth-Moon system. Using craters as probes to the interior, these studies indicate that significant crustal heterogeneities exist in crustal stratigraphy and that the returned lunar samples are not representative of the crust as a whole.[4]

The Moon has a primarily feldspathic crust about 60 km thick on the Earth-facing side overlying a denser interior; any metallic core must be very small (less than 2% lunar mass). The Moon is extremely depleted in indigenous volatile and siderophile elements. It originated nearly 4.5 billion years ago, most likely close to Earth, and underwent primordial, possibly global melting and major differentiation. A solid crust developed about 4.4 billion years ago and may be the best preserved silicate crust remaining in the solar system. Partial melting of a heterogeneous interior with ascent of magmas to the crust and surface continued from at least 4.3 billion years ago until certainly 3 billion years ago and more likely 2 billion years ago. Ancient intense bombardment is evident in numerous craters and multiringed basins but was drastically reduced in intensity after 3.8 billion years ago. Tectonic deformation is mainly limited to the vicinity of major impact basins, a consequence of loading and flexural processes. Many of the basins exhibit significant gravitational mass excesses, a likely consequence of volcanic flooding and crustal thinning (mantle uplift). The Moon currently has minor moonquakes but manifests little other internal activity.

Mars

Other than the Moon, Mars has received the greatest attention from planetary spacecraft. Both the United States and the former Soviet Union have sent a succession of spacecraft to the planet. In the U.S. program the first flyby was Mariner 4 in 1964, which was followed by two more flybys before Mariner 9 became, in 1971, the first spacecraft to orbit another planet. Viking, consisting of two orbiters and two landers, arrived in 1976. Mars Observer was to begin a series of geophysical, geological, and climatological observations in 1993, but radio contact was lost just prior to entry into martian orbit. Although attempts by spacecraft from the former Soviet Union to obtain data from Mars were largely unsuccessful, unique spectroscopic and thermal observations of the martian surface were obtained by the Phobos mission in 1989.[5]

In addition to providing data on atmospheric chemistry and physics, these missions together imaged almost the entire surface at roughly 250-m resolution and local scenes at much better resolution, and also mapped the surface in thermal radiation. Preliminary chemical analysis and life-seeking experiments on the soil were made at the two Viking landing sites. Sparse magnetic data were obtained by Mariner 4 and by some Soviet spacecraft.

The spacecraft results have been supplemented by Earth-based radar, which has yielded information on the elevation and electromagnetic properties of the martian surface, and by visible and near-infrared spectroscopic observations. Samples of Mars are consensually held to exist in terrestrial collections of the Shergotty-Nakhla-Chassigny (SNC) group of differentiated meteorites.

Mars has had a greatly varied geologic history. An ancient, heavily cratered surface has been partly covered by extensive lava plains and huge volcanic edifices, thereby creating a global asymmetry with most of the ancient terrain on one hemisphere and most of the younger surfaces spread across the other (Figure 4.2). The Tharsis province is a locus of volcanism and tectonism that encompasses a quarter of the surface of the planet and rises 10 km above surrounding terrains. The planet has at most a feeble magnetic field, and little is known about the size and constitution of its core because the gravitational contribution from the Tharsis Uplift prevents accurate determination of Mars's moment of inertia. Much of the surface has been modified by tectonic events and by the action of wind, water, and ice. Pervasive dissection of old terrains by seemingly water-worn valley networks suggests that Mars has undergone a major climate change from an initially warm, wet planet with a relatively thick atmosphere to the cold, dry planet observed today. Vast floods appear to have occurred episodically during the planet's history, but their climatic implications are controversial. Seasonal changes in the atmosphere and atmosphere-surface interactions occur, including fluctuations in polar ice caps (water ice with CO_2 frost and silicate dust). The soils, as analyzed at the Viking sites, contain no complex organic material, despite continuous meteoritic infall, because of their highly oxidizing nature. At the Viking sites, the soil is apparently an iron-rich basalt; globally, from Earth-based imaging spectroscopy, the planet's skin appears to contain Fe^{3+}-bearing minerals.

Differentiated Asteroids

Some small bodies in the solar system are differentiated, although definitive evidence is lacking for most. None is known to have been visited by a spacecraft, but their existence is inferred from the presence of differentiated meteorites (basaltic achondrites, irons, and stony irons) and from reflectance spectroscopy and radar studies of asteroids that indicate the presence of igneous mineralogies and free iron (see Chapter 3). Meteorites show that the melting of these small bodies took place very early in solar system history, some 4.56 billion years ago. Differentiated asteroids occur in the main-belt population and are concentrated in the inner to middle belt. While some asteroids melted and became geochemically differentiat-

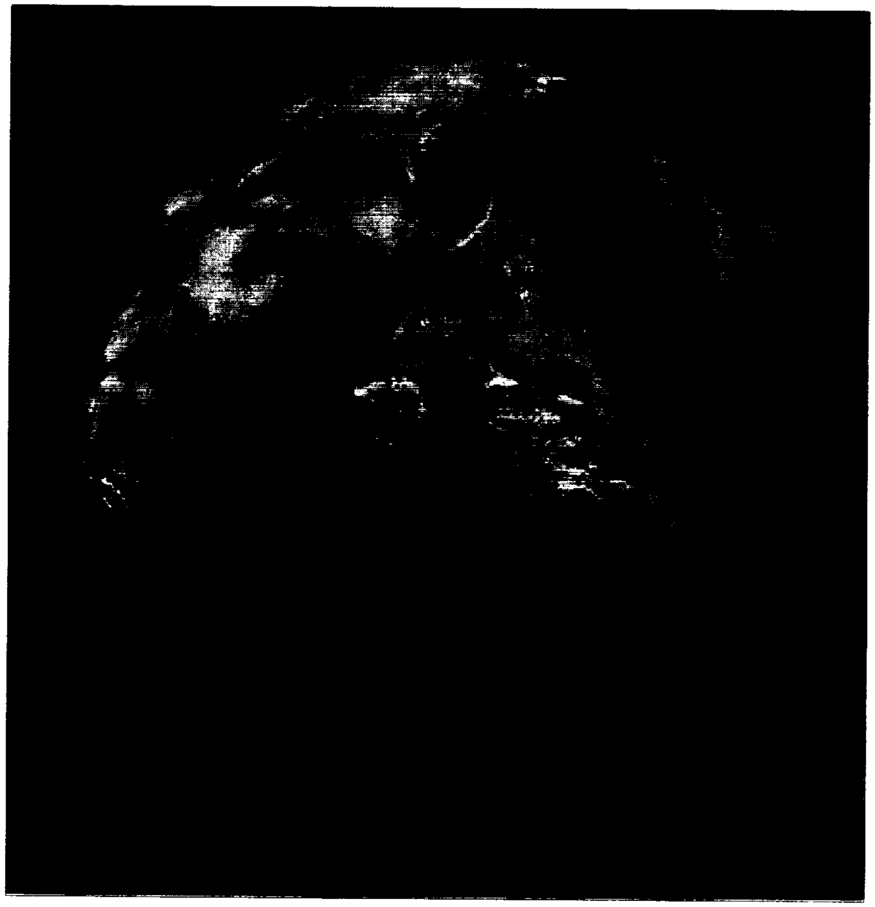

FIGURE 4.2 Cloud-free mosaic of the Valles Marineris hemisphere of Mars. Valles Marineris is a complex canyon system over 3000 km in extent and up to 8 km deep, formed by rifting of the martian lithosphere induced by the Tharsis Uplift. Three major volcanoes associated with the uplift are seen at the western limb. (Courtesy of USGS/NASA.)

ed, many others of similar size escaped such modification. The surface mineralogy of at least one of the largest asteroids, 4 Vesta (260 km in radius), and of several nearby smaller bodies is spectrally similar to that of basaltic achondrite meteorites (displaying strong pyroxene absorptions). Most differentiated asteroids, however, are thought to be fragments or aggregations of fragments of collisionally disrupted precursor bodies. Precisely which asteroid classes, and subclasses thereof, actually represent differentiated bodies remains unanswered.[6]

Outer Solar System

The solid bodies of the outer solar system consist of the satellites of the major planets, the Pluto-Charon system, and several cometary bodies that appear asteroidal owing to their great distances from the Sun. The satellites have been visited by the two Voyager spacecraft, Voyager 1 reaching Jupiter and Saturn in 1979 and 1980, respectively, and Voyager 2 reaching Jupiter, Saturn, Uranus, and Neptune in 1979, 1981, 1986, and 1989, respectively. These flybys provided detailed information on the planets' sizes, masses, and surfaces, including imaging of most of the larger satellites at 1- to 20-km resolution. These bodies were revealed by Voyagers' explorations to be a group of geologically and geophysically diverse worlds, ranging from volcanic Io to frozen Triton, where water is a "rock" and nitrogen and methane apparently drive volcanic activity even on this distant body. Pluto and Charon have been studied to date only through telescopic observations that have determined their sizes, crude albedo variations, and gross surface compositions, as well as Pluto's atmospheric pressure and composition at the current epoch. The interiors of the giant planets, in contrast, have only been indirectly probed through measurements of their gravitational and magnetic fields during spacecraft flybys.

Giant Planet Interiors

As determined by gravitational studies carried out by Pioneer 10 (which reached Jupiter in 1973), Pioneer 11 (which reached Jupiter and Saturn in 1974 and 1979, respectively), and the two Voyager spacecraft, all of the giant planets contain cores (or zones of central concentration) of approximately 10 to 30 Earth masses of material of higher atomic mass than hydrogen and helium. In the cases of Jupiter and Saturn[7] these cores are deep within massive hydrogen-helium envelopes, while for Uranus[8] and Neptune[9] they constitute most of the planet. The cores presumably consist of abundant rock- and ice-forming elements (including Fe, Si, Mg, O, N, and C) and are fluid owing to the great temperatures likely to prevail (although estimates of these temperatures are highly uncertain). No distinct rocky or icy layers are likely to exist on Jupiter or Saturn, although such layers may exist on Uranus and Neptune. Hydrogen and helium may also be dissolved in significant quantities in these cores. These cores may be the seeds to which massive gas envelopes were gravitationally attracted, and in the case of Uranus and Neptune are sites of magnetic field generation. The strong nondipole character of the fields at Uranus and Neptune suggests dynamo generation at relatively shallow depths in these planets such as in pressure-ionized water layers. The jovian and saturnian fields are more axial and dipolar and are inferred to be generated deep in the metallized zones of their hydrogen-helium envelopes.

Galilean Satellites

The Galilean satellites consist of a pair of large ice and rock bodies, Ganymede and Callisto, plus a pair of mostly rocky bodies with very different characteristics, volcanic Io and ice-shrouded Europa. These bodies have been partially explored by Voyagers 1 and 2 and will be studied in some detail by Galileo, which will carry out some imaging at 1-km or better resolution, surface compositional studies, investigations of magnetospheric interactions, and gravitational field measurements that may provide information on the interior structure of at least some of the satellites.[10]

Io, although only the size of Earth's Moon, is the most geologically active body in the solar system due to its strong tidal heating as it is stressed by Jupiter's gravitational field. Volcanoes and geyser-like plumes are continuously active, resurfacing the body with deposits of S, SO_2, and, presumably, basaltic lava on a time scale of thousands of years. Accordingly, no impact craters are yet recognized on Io. Material from the plumes is fed into the jovian magnetosphere; corotating sodium, oxygen, and potassium ions then sputter the surfaces of all the Galilean satellites, adding additional material to the magnetosphere. Thermal emission from Io's volcanic hot spots is monitored from Earth, but an accepted model for Io's global heat budget and volcanological cycle is lacking. Galileo will make only one close pass by Io, because of the potential for radiation damage to the spacecraft if it lingers in this region too long.

Europa is somewhat smaller and less dense than Io. While mainly silicate, it is covered by an icy layer no more than 100 km thick. It is also tidally heated (though not as severely as Io), and tidal theory and observations of fractures on its surface indicate that the ice overlies a liquid water layer and that this ice shell may be rotating slightly nonsynchronously. Available imagery is of insufficient resolution to determine the nature of the abundant surface markings on this satellite, except in a few instances, but fracturing is suspected in many cases. The images display very few impact craters, indicating that Europa is effectively resurfaced on a time scale of a few tens of millions of years. Water or water ice volcanism is possible. Europa's nearly pure ice surface is altered, darkened, and reddened by bombardment by magnetospheric particles and has the highest radar albedo of any nonmetallic surface observed in the solar system.

Ganymede and Callisto are the largest moons of Jupiter. They share adjacent orbits, and their sizes and densities are similar. For both, the ratio of rock to ice is approximately 60% to 40% by mass, and their surfaces are dominated by water ice and lesser amounts of dark, possibly carbonaceous, silicates, but the distribution and identity of the rock components are not known. Both possess impact-generated regoliths whose structures and thermal conductivities are probably complex.

Ganymede's surface is composed of diverse terrain types: relatively dark, ancient, heavily cratered terrain, and relatively bright, less-cratered smooth and grooved terrain. Grooved terrain is composed of long, mountain-like ridges and valleys that occupy domains of Ganymede's surface that have apparently been extended and down-faulted, flooded with water, slush, or ice, and fractured. Ancient craters on Ganymede are highly flattened, sometimes losing nearly all their topography. In comparison, Callisto is nearly uniformly heavily cratered and shows little evidence for resurfacing, and no evidence for extensional grooved-terrain-style faulting.

The crater populations on both bodies are distinct from those expressed on the heavily cratered terrains of the terrestrial planets, in that they largely lack craters greater than 60 km in diameter. Most distinctive on Callisto's surface are large flattened impact basins surrounded by numerous fracture rings extending radially for hundreds to thousands of kilometers. Sections of similar fracture patterns are seen within the ancient cratered terrains on Ganymede. The differences in the evolutions of Ganymede and Callisto are not understood, but tidal heating may have played a role, given that Io, Europa, and Ganymede all partake in an orbital resonance, while Callisto does not. Ganymede is thought to be differentiated, while Callisto's internal structure is unknown.

Satellites of Saturn

The icy satellites in the saturnian system share some of the characteristics of the Galilean moons, including a diversity of volcanic and tectonic activity, but with the exception of Titan, form a class of smaller objects: mid-size icy satellites. Their densities are consistent with ratios of bulk ice to rock of 60% to 40% or more, they are all generally heavily cratered, and with the exception of Iapetus, their surfaces are spectrally dominated by water ice. The approved Cassini mission should complete the reconnaissance of these bodies and allow detailed studies of at least a few of them. They can be discussed as three similarly sized pairs.

Mimas and Enceladus are inner moons of approximately 500-km diameter, but they are very different from one another. Mimas's surface is dominated by craters and a complex set of fractures and shows no evidence of endogenic activity. It may have reaccreted from one or more catastrophic disruptions owing to collisions with large cometary impactors. Enceladus, in contrast, has regions devoid of craters (at Voyager resolution) and is the most reflective object at visible wavelengths in the solar system. An orbital resonance with the more massive Dione leads to limited tidal heating of Enceladus's interior and possibly to periodic resurfacing. Low-melting-point ices such as those composed of ammonia and water may also be involved, but these have not yet been identified spectroscopically.

Dione and Tethys are both approximately 1000 km in diameter. Each shows evidence for resurfacing in the geologic past. The chemical composition of the resurfacing ices is not known. Tethys has a large crater nearly half its diameter across and a globe-girdling canyon system approximately 90° away from the crater, to which the canyon's formation may be owed.

Rhea and more distant Iapetus, both approximately 1500 km in diameter, are another study in contrast. Rhea is largely heavily cratered, with some faulted regions, but shows little evidence of resurfaced areas. Iapetus, although poorly imaged by Voyager, is also heavily cratered but displays a striking hemispheric dichotomy, with one-half of the surface being bright and icy whereas the other is quite dark and probably carbonaceous. It is of considerable interest whether this dark material is endogenic (has erupted from the interior) or exogenic (a layering of dark dust from outermost Phoebe [see the section "Small Satellites," below]). Rhea and Iapetus, because of their sizes and distances from Saturn, best express the ancient crater population due to heliocentric bombardment in the saturnian region.

Titan

The largest satellite in the saturnian system, comparable in size to Ganymede and Callisto at Jupiter, and the possessor of the densest satellite atmosphere by far, Titan is a particularly interesting object. Study of this satellite as a solid body is impeded, as it is for Venus, by an optically obscuring haze. Its interior has a ratio of rock to ice of about 60% to 40% by mass and is probably differentiated. Because Titan formed around Saturn, ammonia and methane were presumably incorporated and probably contributed to its surface and atmosphere. Atmospheric evolution models suggest an ocean of methane, ethane, and nitrogen. Chemical reactions may create solid hydrocarbons and other organic materials, and these may dominate the surface; there is a potential for further chemical evolution. Earth-based radar shows that a large fraction of the surface cannot be covered with a low-reflectivity ocean, as predicted for a low-molecular-weight liquid hydrocarbon, but the liquid may contain highly scattering material or be stored in pore space within a regolith. Cassini's planned radar observations and other data, including some imaging from the Huygens probe, will greatly advance the state of knowledge of this satellite.

Uranian Satellites

The satellites of Uranus were observed during Voyager 2's flyby; useful densities were obtained for the five major moons, and the half of each satellite accessible to observation (their south poles were all nearly Sun-pointed in 1986) was studied at resolutions ranging from several kilometers to better than 1 km for Miranda. The five major moons are mid-size icy satellites most directly comparable to those of Saturn, and as is generally true among outer-planet satellites, several exhibit a remarkable degree of tectonic activity and resurfacing (presumably by volcanic processes) for small icy objects. As for the mid-size saturnian satellites, non-water-ice volatiles probably play a role in these processes, and possible energy sources include radionuclides, orbital resonances, and breakup and reaccretion. The uranian satellites as a group are darker and denser than the mid-size saturnian satellites (see Table 4.1), indicating important differences in composition and origin between the two groups.

Oberon and Titania are the outermost and largest pair. Both are heavily cratered. Titania displays resurfaced plains and a canyon system that is not as extensive as the one on Tethys. Oberon was imaged at a resolution too poor to make definitive statements regarding its resurfacing history, but regions within several large craters contain dark deposits that may be related to the dark material on Iapetus (although the deposits are not as dark). The rest of the surfaces of these satellites appear icy. Water ice is currently the only material identified (by ground-based reflectance spectroscopy) on any of the uranian moons.

Ariel and Umbriel, the next pair inward, are somewhat smaller. Umbriel is heavily cratered, appears to have been geologically active during its recorded history, and is relatively dark. Ariel is the brightest of the uranian satellites and is extensively modified by plains formation, ice volcanism, and large-scale faulting and vertical crustal motion. Ariel is not currently in an orbital resonance that would have caused it to be tidally heated, but may have chaotically evolved through one or more resonances in the geological past.

Innermost Miranda is a relatively small moon that shows a remarkable diversity of geologic terrains. Roughly one-half of the satellite is cratered and covered with a substantial regolith. The rest has experienced a complex series of volcanic and tectonic events, resulting in terrains unique in the solar system. Miranda is deep enough in the gravity well of Uranus that it has probably been catastrophically disrupted and reaccreted, and such an event has been suggested as the cause of Miranda's variegated appearance, although an epoch of tidal heating may also have been responsible. Currently there are no planned missions to return to the uranian system.

Triton

Of the major satellites visited by Voyager during its encounter with Neptune, Triton is one of the most remarkable. It is in a retrograde, inclined orbit, suggesting capture, and is the most rock-rich icy satellite other than Europa, with the fraction of rock approaching 70% by mass. Triton is the only satellite save Titan with known substantial amounts of nonwater volatiles; N_2, CH_4, CO, and CO_2 have been identified in ground-based infrared reflectance spectroscopy, and N_2-ice dominates. Triton exhibits, within the small region observed in detail by Voyager, a wide array of tectonic, volcanic (see Figure 4.3), and atmospheric processes. Triton's large southern polar cap contains active geyser-like plumes, whose composition and mechanics are unknown, as well as numerous dark streaks that are probably deposits of former plume particles. Eruptions from volcanic vents are seen, as well as expanses of relatively smooth resurfaced terrain. A large portion of Triton's surface is characteristically dimpled and may

TABLE 4.1 Physical Characteristics of the Planets and Their Major Satellites

Planet	Major Satellites	Radius (km)	Density (g/cm^3)	Surface Composition
Mercury		2,439	5.43	Rock
Venus		6,051	5.25	Rock
Earth		6,378	5.52	Rock, liquid water
	Moon	1,738	3.34	Rock
Mars		3,393	3.95	Rock, water ice
	Phobos	~11	~2.2	Carbonaceous?
	Deimos	~6	~1.7	Carbonaceous?
Jupiter		71,398	1.33	—
	Amalthea	~100	—	Sulfur/rock?
	Io	1,815	3.57	Rock, sulfur, SO_2
	Europa	1,569	2.97	Water ice
	Ganymede	2,631	1.94	Dirty ice
	Callisto	2,400	1.86	Dirty ice
Saturn		60,330	0.69	—
	Janus	~100	—	Water ice?
	Mimas	197	1.17	Water ice
	Enceladus	251	1.24	Water ice
	Tethys	524	1.26	Water ice
	Dione	559	1.44	Water ice
	Rhea	764	1.33	Water ice
	Titan	2,575	1.88	Dirty ice/liquid hydrocarbons and N_2?
	Hyperion	~130	—	—
	Iapetus	724	1.18	Dirty ice
	Phoebe	110	—	Ice/carbonaceous Carbonaceous?
Uranus		26,200	1.15	—
	Puck	77	—	Carbonaceous?
	Miranda	236	1.15	Dirty ice
	Ariel	579	1.56	Dirty ice
	Umbriel	585	1.52	Dirty ice
	Titania	789	1.70	Dirty ice
	Oberon	761	1.64	Dirty ice
Neptune		25,230	1.55	—
	Proteus	208	—	Carbonaceous?
	Triton	1,353	2.06	Nitrogen ice, CO_2 ice
	Nereid	170	—	Dirty ice
Pluto		~1,180	~1.9	N_2 ice, organics
	Charon	~620	~1.9	Water ice

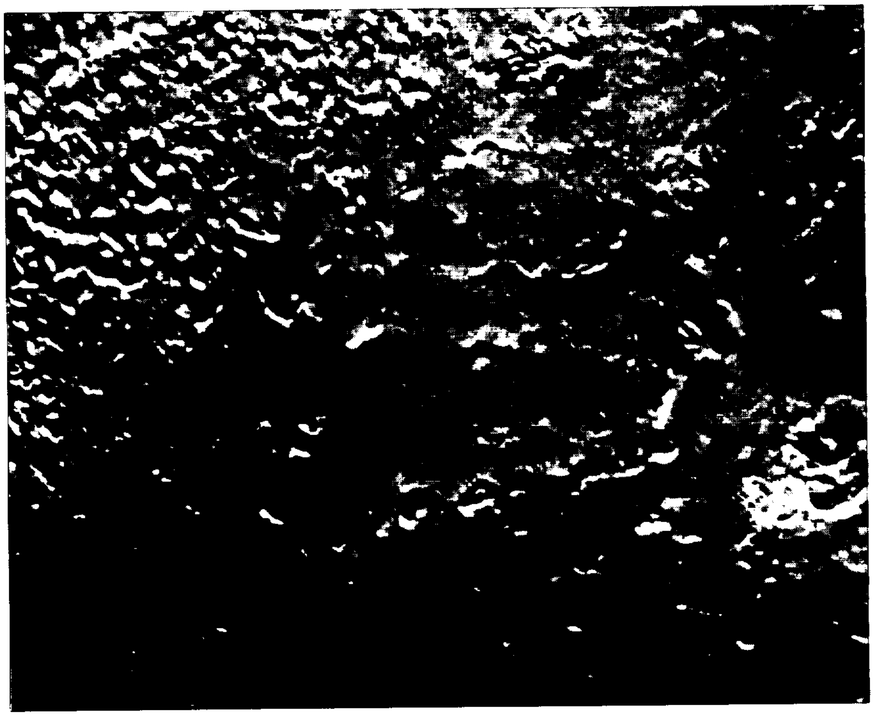

FIGURE 4.3 Volcanic terrain on Triton. Eruptions of icy lava of unknown composition have buried preexisting terrain. Several possible vents for the eruption are seen, including one surrounded by a lower-albedo deposit. Only a few impact craters are apparent, attesting to continuing geological activity on this distant satellite. The image is some 550 km across. (Courtesy of NASA.)

have been subjected to intense density-driven overturn. Triton has an extremely complex "seasonal" cycle, leading to the possibility of climatic changes on a wide variety of time scales. Triton's surface is relatively youthful, with only about 180 craters counted at Voyager resolution. As with the other icy satellites, the energy sources for the observed volcanic and tectonic activity are not well understood. Triton's energy sources may well be even more complex, involving past catastrophic tidal heating associated with its capture from solar orbit. Currently, there are no planned missions to return to the neptunian system.

Pluto and Charon

Pluto and Charon remain the only major outer solar system objects not visited by a spacecraft.[11] In spite of this, information is available in many areas as the result of intensive telescopic observations, including detailed studies of the recent series of mutual eclipses and transits, stellar occultations, ground-based and Hubble Space Telescope images, radiometric measurements, and infrared spectra. These observations have provided reasonably accurate indications of size, albedo, system mass, surface composition (different for the two objects), atmospheric pressure (or upper limits) and composition, and surface temperature, and even crude albedo maps. Pluto appears similar to Triton in size and density. Charon is fully half Pluto's size, and the angular momentum density of the duo is the greatest for any planet-satellite pair in the solar system, including the Earth and Moon.

Infrared spectra of Pluto indicate an icy surface and an atmosphere dominated by nitrogen, with minor amounts of CO and CH_4. Charon's surface, in contrast, is dominated by water ice. Pluto's surface temperature has been estimated from data returned by the Infrared Astronomical Satellite and by millimeter and sub-millimeter radio measurements, but these do not agree. Fresher (i.e., brighter) frosts and ices are concentrated on Pluto in a southern polar cap and northern region, while the equator is generally darker; it may have accumulated organic material created from methane by ultraviolet or cosmic-ray irradiation, or other radiation-damaged ices. Pluto, like Triton, undergoes complex seasonal and orbital variations, leading to the possibility of changes in climate and surface on a wide variety of time scales.

Currently there are no approved missions to the Pluto-Charon system, although a reconnaissance flyby has been proposed for the time frame covered by this report.

Kuiper Belt Objects

Numerical studies indicate that long-lived objects may populate a Kuiper Belt of comets beyond ~45 AU. As of this writing, seventeen ~200-km-diameter objects have been discovered in near-circular, low inclination orbits with semi-major axes between 40 and 45 AU. Objects in the Triton- and Pluto-size class, and thus no longer primitive, may be discovered in the future.

Small Satellites

Numerous smaller, generally irregularly shaped satellites are found in orbit around Mars and the giant planets. Some are in distant orbits suggesting capture, while others are close to their primaries and may be fragments or reaccreted remnants of earlier moons. Many of these latter satellites were discovered by Voyager and are intimately related to the ring systems of the giant planets.

Phobos and Deimos, approximately 20 km wide, are the two moons of Mars. Spectrally they resemble the darkest asteroids and may have been captured or formed from material left over from the accretion of Mars. Alternatively, they may be reaccreted ejecta from large impacts on the planet's surface.

Jupiter is notable for having two groups of satellites in irregular, distant orbits. One group is in a prograde orbit and the other in a retrograde orbit; members of both groups resemble dark C-type asteroids spectrally and are thought to have been captured early in solar system history. Amalthea orbits interior to Io, and Voyager images show it to be very irregular and red, probably as a result of having been coated with material ejected from Io. Two smaller inner moons are associated with the jovian ring, and another orbits between Amalthea and Io.

Hyperion and Phoebe are two small (<400-km-diameter) moons of Saturn. Hyperion is a cratered fragment (no longer spherical) and is chaotically tumbling while orbiting between Titan and Iapetus; Phoebe, with a distant retrograde orbit, has a reflectance spectrum similar to that of a C-type asteroid and was presumably captured. A plethora of smaller icy moon fragments reside in the saturnian system; two are co-orbital, three are satellite Trojans (orbiting at the Lagrangian points of Dione [one satellite] and Tethys [two satellites]), and several are associated with the rings (as shepherds or gap-clearers).

At Uranus a group of smaller satellites extends inward from Miranda; some of these are among the planet's rings. A similar system is present at Neptune inward of 5 planetary radii. Neptune also possesses Nereid, which follows a distant, inclined, and highly eccentric orbit. Little is known about this enigmatic body, other than its size (170-km radius), overall shape (roughly spherical), albedo (higher than that of typical outer solar system asteroids), and color (spectrally neutral). It may have been captured or may be a primordial moon of Neptune perturbed to its present orbit during the disruption of the neptunian system by Triton.

SCIENTIFIC THEMES

Interior Structure and Dynamics

The vast interior regions of planets are virtually unknown for every object. Progress in this area has been slow even for the best-explored planet, Earth. The Moon is the only other body for which even a crude interior model has been constructed from seismology.

The interiors of the terrestrial planets and most major satellites of the outer planets have undergone solid-state convection throughout most if not all of their lifetimes. Direct evidence for convection exists for Earth, and similar inferences can be made for Venus, but the argument is theoretical for the other objects, and the thermal structures for all are uncertain. The details of today's convective pattern within Earth, and the evolution of this pattern, are intensely debated: for the other planets and satellites, either now or in the past, such information is unavailable.

During and immediately after planetary accretion, most bodies are believed to undergo primary differentiation aided by high temperatures and extensive melting or even vaporization. In terrestrial planets and smaller bodies of similar composition, this differentiation involves the formation of an iron-rich core, a silicate mantle, and a light, primordial crust. The pressure and temperature conditions during this separation will be reflected in the resulting chemistry and dynamics of the differentiated body. In icy bodies, the most important differentiation is that of ice from rock, with both parts possibly undergoing additional differentiation. In giant planets, there is an uncertain degree of mutual separation of the three components: rock, ice, and gas; within the latter component at high pressures (easily achieved within Jupiter and Saturn), considerable uncertainty exists about the possible presence of metallic hydrogen and the miscibility of helium in that medium. Thus, the extent of differentiation is poorly understood in all bodies and even totally unknown in many.

It is important to place limits on the nature of planetary and satellite differentiation because it tells about the bulk composition as well as the state of the body during and immediately after accretion: the degree of differentiation therefore sets the initial conditions for all subsequent evolution.

Data concerning interior structure are extremely difficult to obtain, but are worth considerable effort to achieve for even a few bodies. All solid planets possess brittle outer layers in which stress is stored and then released as seismic events (earthquakes). Although the level of seismic activity is not known for any body other than Earth and the Moon, even conservative estimates indicate levels of activity for most bodies that should be detectable in situ and should be diagnostic of structure. The waves produced by seismic events travel through a planet and can be detected at both regional and global distances, thereby providing essential information on crustal and mantle structure and the existence and nature of any core. In accord with terrestrial experience, this is the best way to determine internal structure.

Two kinds of precise positional measurements provide information on internal structure and dynamics. The first is a very accurate determination of the spin angular-momentum vector of a planet (both amplitude and direction) to monitor length-of-day changes, nutation, and precession. In some circumstances, such measurements can allow determination of the planet's first-order interior structure and whether the planet has a liquid core, as well as the nature of core-mantle coupling; this has been done for the Moon and could be done for Mars and Mercury.

The second type of measurement, which is regional and is similar to that made possible by the Global Positioning System on Earth, can lead to the detection of small relative crustal movements (of the order of 1 cm/yr or, possibly, 1 mm/yr in the future). Such measurements could provide interesting new information for a planet with suspected active tectonism, such as Venus and possibly Mars.

Once the gravitational fields associated with a planet's central mass and its rotational bulge are removed, a higher harmonic field remains whose amplitude

C-2.

and character are diagnostic of mantle and lithospheric properties. From the correlation of this latter field with topography, one can infer either crustal thickness or the nature and extent of dynamic support (e.g., upwelling mantle beneath "hot spot" volcanoes). Constraints on internal structure can be deduced, although such interpretations are not unique. The use of this technique requires a determination of both the gravitational field and the topography, preferably to a spatial resolution of a few hundred kilometers or better.

The conductive and advective flow of heat through a planet's surface is a primary indicator of the global energy budget—both the sources of energy available (radiogenic, accretional, tidal, gravitational, and chemical heating) and the mechanisms that control its release (convection, conduction, volcanism, hydrothermal processing, and so on). Knowledge of heat flow provides important constraints (through inferences about internal temperatures) on the rheology and dynamic behavior of deeper layers of a planet, on both global and regional scales. Higher and lower heat flow may control the level of volcanic activity, permafrost and ice cap stability, and so forth. Heat flow measurements have been obtained in situ only on Earth and the Moon, while remote sensing in the infrared has proved successful for gathering data about volcanoes on Earth and Io and has measured the global heat flow of the giant planets. Although technically difficult and possibly nonrepresentative, a single such measurement could prove valuable to understanding a given planet.

The outer regions of the giant planets are composed of gas, but their interiors consist of varying proportions of metallic hydrogen-helium and rock- and ice-forming elements. Variation in composition with depth within these bodies is produced by the original process of accumulation and any subsequent rearrangement through flow and gravitational separation. This layered composition, when coupled with the planetary rotation, causes the mass distribution within the planets to have an oblateness that varies with depth. This characteristic is reflected in their gravitational fields, which give the means of determining the internal compositional structure of the outer planets. The gravity field can at best constrain the density profile, so that an equation of state must be known in order to test any compositional hypothesis against actual gravity data. The range of compositional hypotheses is somewhat constrained by atmospheric observations, even though many of the cosmically abundant constituents are frozen out at atmospheric temperatures.

To improve knowledge of the internal structures of the outer planets, work is needed in several areas. Improved knowledge of gravitational fields and planetary precession periods is important. Theoretical and laboratory work on equations of state at high pressures needs to be continued. Theoretical and laboratory work on heat transfer and mixing in fluids with phase changes needs to be further pursued and has much overlap with terrestrial geophysics. Ultimately it may be possible to use the free oscillations of a planet to probe its internal density structure, much as helioseismology has been used to obtain some properties of the solar interior. It is not known whether deeply propagating internal waves (either acoustic or gravity) are excited to sufficient amplitudes to be observable at the surfaces of the outer planets. Because of the great potential value of probing depths that are otherwise not accessible, an observational search for wave modes is important. Improved determinations of heat flow as a function of latitude would also provide valuable constraints on atmospheric circulation and internal structure.

Key Questions

Key questions with respect to interior structure and dynamics include (in no particular order) the following:

- Which planets and satellites have cores, and what are the current compositions and states (liquid or solid) of these cores?
- What is the principal layering throughout the rest of these bodies, and is it due to phase transformations or compositional changes?
- What processes operated during planetary and satellite differentiation that led to layered structures, and what were the time scales for differentiation? Was differentiation contemporaneous with accretion or did it extend to later times?
- What was the thermal state during differentiation? In particular, which bodies had oceans, including magma oceans for terrestrial bodies?
- What are the consequences of this primary differentiation for surficial volatile reservoirs, the generation of magnetic fields, and the initiation of deep (mantle) convection and tectonics?
- What are the heat flows of the terrestrial planets and icy satellites? Do they vary appreciably over the surface of a given body?
- What are the higher-order gravity fields of the terrestrial planets and satellites, especially Mars, the Moon, Mercury, and Io?
- What is the distribution of heat flow with latitude for the giant planets?
- Can free oscillations of the giant planets be detected and used to constrain their interior structures?
- What are the equations of state for materials of planetary interest (metal, rock, ice, and gas)?

Planetary Magnetism

For more than a millennium Earth has been recognized, to varying degrees, as a magnet. However, it was not until the invention of radio telescopes that it was possible to infer that at least one other planet, Jupiter, also possessed a strong, internally driven magnetic dynamo. Since then, planetary probes have added four other planets to this list: Mercury, Saturn, Uranus, and Neptune. The fields produced by these planetary dynamos are quite varied. The magnetic field of Mercury appears to be a miniature version of Earth's, with a typical field strength of 1% of the terrestrial value. At the other extreme, Jupiter's and Saturn's magnetic moments are much larger than Earth's, with typical surface field strengths for Jupiter being 10 times those of Earth and Saturn. Saturn's magnetic field—unlike the magnetic fields of all the other planets—is axisymmetric and aligned with the rotation axis (within observational uncertainty) for all observed orders: dipole, quadrupole, and octupole. Uranus and Neptune also have unusual fields, with highly oblique tilts of their dipole axes to their rotation axes and a rich harmonic content.

Planetary magnetic fields are generated as electrical currents flow through the planet's interior. Owing to the interior's finite resistivity, these electrical currents will decay unless they are maintained by the motion of an electrically conducting fluid in the interior. In a planetary dynamo, the decay of the magnetic field and its generation are in approximate equilibrium; accordingly, magnetic forces must play a significant role in the interior's dynamics. Moreover, since, to first order, the magnetic field is frozen into the convecting fluid, temporal and secular variations of the field should give otherwise unobtainable insights into the interior's fluid motion.

The nature of the magnetic fields is determined by the properties of the magnetic dynamo in each of these planets: its location and size, the convective pattern of the conducting fluid, the strength of the energy source driving these flows, and the fluid's electrical conductivity. Thus, planetary magnetic fields provide important clues to the physical nature of planetary interiors. At present, these clues remain only hints rather than hard constraints because models of planetary dynamos are still in the developmental stage. Over the last few years, however, these models have made significant progress, paced to some extent by the increasing power of supercomputers.

Over the course of the history of a planet, the interior's thermal state evolves. Accretion and differentiation (if it is not contemporaneous with accretion) provide intervals of heating. The onset of solidification of the liquid core provides both gravitational energy, as the denser material settles, and latent heat. Thus, a planet's magnetic field should be a sensitive indicator of the dynamical state of its interior. A record of the magnetic and, by inference, thermal history is preserved in the rocks that were extruded onto the surface and cooled below the magnetic blocking temperatures.

Measurements of the remanent magnetic field from orbit and the deduction of magnetic paleointensities from returned lunar samples have been instrumental in developing a tentative magnetic and thermal history for the Moon. Thus on those planets whose surfaces are cool enough for long-term preservation of magnetic remanence, we should seek to deduce the ancient magnetic field both from magnetic surveys and from returned samples. Since magnetic fields can suggest the present and past dynamical state of a planet's fluid interior, it is important, wherever possible, to characterize these fields. In general, this will require measurements in low-altitude polar orbit and repeated sampling. For Earth, surveys conducted once per decade have proven adequate, and it is expected that core dynamic effects could be seen over decadal time scales for Mercury (and possibly for Mars if it has an internally generated field).

Key Questions

Key questions with respect to planetary magnetism include (in no particular order) the following:

- What are the natures of actively generated planetary magnetic fields to high order as well as their variations over time?
- What are the remanent magnetic fields of planetary surfaces of various ages, especially those on Mars?
- What are the implications of the differing magnetic field structures of the giant planets for their internal structures and dynamos?

Tectonics

While the interior of a planet or satellite may often be considered to behave like a viscous fluid on a geologic time scale, the outer layer, or lithosphere, of a planet or satellite is cooler than the interior and may respond to deeper convective motions by a combination of elastic, plastic, and brittle deformation. As one important example, Earth's oceanic lithosphere couples to the mantle's convective flow and descends into the mantle along what are identified as subduction zones. In response, new oceanic lithosphere is created by conductive cooling at oceanic spreading centers.

Tectonic styles within lithospheres vary from discrete fault structures such as graben, to more distributed strain patterns such as folding, or combinations such as wrinkle ridges. Stress sources may be localized or spatially distributed. Some may be global in scale. Examples of the latter include tides raised on a body due to its eccentric orbit about its primary; this has profoundly affected Mercury and many satellites in the outer solar system. Other global-scale stresses can be generated by rotational changes (despinning), secular cooling (which may involve phase changes), and internal convective motions.

Localized stress sources include volcanic surface loads and intrusions, topography itself, and small-scale convection within upper mantles. All have been extensively studied in terrestrial examples.

The lithospheres of other planets and satellites seem to be complete shells (one-plate planets). Nevertheless, they may still develop large-scale tectonic structures, for example, the Valles Marineris rift system on Mars. The degree of mobility of Venus's surface is being actively investigated, but the surface has clearly been extensively deformed tectonically in response to motions within the underlying mantle.

Tectonic activity has occurred in the past on various satellites of the outer planets (e.g., Ganymede, Tethys, and Ariel) and is probably occurring at present on Io, Europa, Enceladus, Triton, and possibly Pluto. Tectonics in many outer solar system satellites may be principally a response to heating or cooling and subsequent volume change of the interior and lithosphere, induced by radiogenic heating by silicates or by orbital tidal effects. How large a role mantle convection plays in these tectonics is unclear. In at least the case of Europa, tidal stresses play a direct role in fracturing the surface.

The nature and spatial distribution of present tectonic (and perhaps volcanic) activity are indicated by the distribution of seismicity and are thus important to measure. Tectonic features themselves also offer vital clues to lithospheric, and sometimes crustal, structures and heat flows, because the size and pattern of the features are sensitive to rheologic variations, and hence to temperature gradients and compositional layering.

Key Questions

Key questions with respect to tectonics include (in no particular order) the following:

- Which terrestrial planets and icy satellites are still actively convecting internally? What are the style and structure of the convective patterns within these bodies? What are the influences of internal (chemical, phase, and geologic) structure and previous thermal history?
- How much heat is transported convectively, and how much is advected by partial melting of mantles and the subsequent ascent of magma?
- How are viscous mantles and lithospheres coupled within the different solar system bodies? What is the role of chemistry and volatiles in this coupling? Under what conditions can the lithosphere be recycled into the mantle? What conditions are necessary for Earth-like plate tectonics?
- How do global- versus local-scale processes contribute to the distribution of planetary seismicity and observed tectonics?
- What are the tectonic histories of the different planets and satellites? Specifically, why are the tectonic histories of Venus, Earth, and Mars so markedly distinct?
- Why does tectonic activity on the terrestrial planets differ from that of the icy satellites? How much is a matter of stress sources, and how much is a matter of the compositional ratio of rock versus ice?
- What do the different tectonic histories imply for accretion and the subsequent evolution of the interiors, and for lithospheric and crustal thicknesses and heat flows, and how they have changed with time?
- What is the cause of the global dichotomy on Mars? Can it be accounted for by internal convective activity?

- How did Venus's highlands and the Tharsis and Elysium bulges on Mars form, and what do they imply for the state of stress in the crust and the dynamics of the interiors of the two planets?
- What causes vastly different tectonic styles on various icy satellites such as Europa, Ganymede, Enceladus, Miranda, and Triton?

Formation and Evolution of Primary Crusts

The crust of a planetary body is the solid surface seen by remote sensors and landed on by spacecraft. The crust is thus our principal interface with the body. All planets and major satellites have differentiated, and their crusts are thus processed materials. The product is of course determined by the body's initial composition as well as the processes active during differentiation and subsequent evolution. Primary crusts include the lunar highlands, probably the cratered terrains of Mercury and Callisto, and possibly the heavily cratered regions of Mars. Secondary crusts are derived from remelting of the interior (e.g., Earth's oceanic crust, the volcanic plains of Mars and the Moon, and most of Venus) or by recycling of crustal materials (e.g., the continental crust of Earth).

The elemental and mineral composition of the crust reflect its formation and evolution. Measurements of elemental abundances provide information on bulk composition, which is related to origin, while detailed measurements of trace-element and isotopic abundances, where analytically feasible, yield clues to evolution and age (normally requiring laboratory analyses of a sample). Mineral and ice composition provides information about lithologic type and the processes required for crustal origin, oxidation state, equilibrium-disequilibrium conditions during formation, and extent of volatile interaction.

An assessment of the chemical and mineralogical composition of the crust at several scales is fundamental to understanding the crust's origin and evolution: global analyses (on scales of hundreds of kilometers) yield bulk composition, regional analyses (on scales of a few to a hundred kilometers) provide information on geologic context, local analyses describe individual environments, and analyses of single samples provide the means to quantify and date events. Global and regional assessments can be accomplished with a variety of remote-sensing capabilities that operate at different scales, local analyses are accomplished with in situ measurements, and detailed investigation of samples (petrography and precise analyses of major, minor, and trace elements and their isotopes) normally requires that samples be returned to Earth.

Key Questions

Key questions pertaining to the formation and evolution of primary crusts include (in no particular order) the following:

- Does Mercury have a primary or secondary crust (i.e., is it predominantly feldspathic or is it made of basaltic flows and intrusions)?
- Are the heavily cratered uplands of Mars remnants of an earlier primary crust or a reworked ancient secondary crust?
- Did formation of the lunar primary crust include an extensive phase of plutonic activity in addition to a primary "magma ocean" differentiation? If so, what is the origin of these early magmas (e.g., remelting of the mantle and/or crust or of a primitive interior)?
- Does Venus have any remnants of a crust comparable to evolved terrestrial continental crust? What accounts for the high dielectric material at elevated topography?
- Are there any recycled secondary crusts other than that of Earth?

Volcanism and Mantle Evolution

The surface layers of any solid solar system object display that body's history of successive events, such as volcanic eruptions and impacts. Each event destroys some part of the previous record, but by examining the crustal record we can partially reconstruct the evolution of the body. The success with which this can be achieved depends on the complexity and completeness of the record, which varies from body to body. The crust is also the part of the solid planet that is most accessible and on which measurements are made, so that understanding it is crucial.

Secondary crusts are derived from mantles, mainly by melting processes, over some period of time. How a crust evolves is affected by volcanism, by the dynamics of the interior, through bombardment with asteroidal and cometary debris, and by sedimentary and depositional processes. The volcanic and deformational history is, in part, a reflection of more deep-seated conditions in the mantle, in particular its thermal and dynamical state. Erosional and depositional history provides information on the history of the atmosphere, and may furnish insights about mantle evolution insofar as it depends on tectonic activity and the planet's outgassing history. The very existence of atmospheres on Earth, Mars, and Venus, and possibly Titan, Triton, and Pluto, may depend on their respective volcanic histories. Therefore, reconstruction of the crustal histories of solid bodies is, not surprisingly, a prime objective of planetary exploration.

For any particular object, we wish to know that body's volcanic, tectonic, bombardment, and erosional and sedimentation histories. Each planet has a unique history; for instance, the bulk of the Moon's crust was formed early from a global melting event, whereas Earth's crustal formation is ongoing from mantle recycling mechanisms. Clues concerning these histories are embedded in each object's three-dimensional configuration of near-surface rocks (or ices) as well as the chemistry, mineralogy, lithology, and relative ages of different rock units. The chemical composition of a planetary or satellite surface reflects that body's evolution, because the composition is the product of the initial differentiation, subsequent igneous activity, impact mixing, and sedimentary processes.

For silicate planets and differentiated asteroids, compositions of mantle-derived basaltic melts contain information about mantle composition and evolution. For icy satellites, compositions of nitrogen- or carbon-bearing ices emplaced as volcanic units contain information about ice-mantle compositions and evolution. Regional differences in composition may reflect broad tectonic regimes (e.g., on Earth, basalts at mid-ocean ridges and andesites at convergent plate boundaries) or epochs of distinct magmatic activity (e.g., the lunar highlands and maria).

A regolith of rock fragments pulverized and laterally transported by meteoroidal impact is developed on planetary objects that lack any appreciable atmosphere (e.g., the Moon, Mercury, and the asteroids). Investigation of such regolith can yield valuable information pertaining to several different issues, including the exogenic aspects (see below) and crustal evolution. A regolith sample contains indigenous rock fragments from a wide geographical area; although the geological context of such fragments is lost, they contain a record of the lithic and geochemical units, particularly those near the sampling site.

Impacts also eject, within limits, material from planet to planet. Lunar and probable martian meteorites are known, but mercurian and venusian samples are much less likely to be collected as meteorites. Obtaining documented martian samples should prove or disprove a martian origin for the SNC meteorites and also enhance the value of the SNCs in that they could be placed in the proper geologic context. In addition, obtaining samples of other igneous or sedimentary terrains (i.e., the ancient martian highlands) would greatly augment our understanding of martian geologic evolution.

Experimental and theoretical studies of rock and ice systems are also crucial to understanding the mineralogy and petrology of returned or providential (meteoritic) samples and the volcanic terrains on various bodies.

Key Questions

Key questions with respect to volcanism and mantle evolution include (in no particular order) the following:

- What varieties of volcanic activity exist within the solar system, and how are they determined by composition, temperature, and other factors? What are the compositions of the various ice-volcanic terrains in the outer solar system?
- What are the sequence and nature of the materials erupted onto the different planetary surfaces, and what do they tell about the mineralogical, chemical, and physical properties of the interiors of different bodies and how they have changed with time?
- How are the origins and evolutions of atmospheres tied to volcanic, sedimentary, and erosional histories?
- Did Venus undergo global resurfacing around 500 million years ago, and, if so, what was the cause of this event? Why has most of the volcanism on Mars been restricted largely to the Tharsis and Elysium regions?

• What volcanic processes currently operate on Io, Triton, and, perhaps, Titan, Enceladus, and Europa? What are the resurfacing rates?

• What are the origins of the compositionally and chronologically diverse suite of lunar basalts and pyroclastic materials?

• Were the grooved and smooth terrains on Ganymede resurfaced by water in the solid or liquid (or intermediate) state?

• Has Pluto been as volcanically and tectonically active as Triton? Do their crustal compositions imply similar or divergent internal evolution? Are their surface compositions consistent with the cosmochemistry of planetesimals accreted in the roughly 30- to 40-AU region of the solar nebula?

Impact Cratering

Impact cratering is a fundamental process affecting virtually all planetary surfaces.[12] Craters are the result of collisions between members of a population of projectiles or impactors and a larger body that has a rigid surface. Planetary bodies with active interior processes creating or recycling the crust (e.g., Earth, Venus, Io, probably Europa, and perhaps Triton) have eliminated some or all of the early cratering record. Other bodies with less active interior engines (e.g., Mars, the Moon, Mercury, and Ganymede) exhibit a historical record of both the early and the late cratering events. On these bodies, impact cratering played a pivotal role in shaping the early crust.

Since the recognition that major impacts on Earth have had a dramatic effect on geological and biological evolution and, probably, climate change, understanding the physics and character of impact processes has gained additional relevance. Cratering affects planets and satellites themselves. The early heavy bombardment possibly influenced planetary evolution and differentiation, with large impacts perhaps inducing volcanism. Nearly catastrophic collisions may beget satellites, grossly alter planetary and satellite spins, and perhaps markedly modify mantle compositions. In addition, collisions may damage biospheres, influencing, for example, the evolution and possibly even the origin of life on Earth.

On perhaps a smaller scale, extraterrestrial impacts are responsible for launching the variety of meteorites received by Earth and studied in terrestrial laboratories to unlock these clues to solar system origins. Understanding the biases of the delivery method and identifying the possible source bodies are of fundamental importance.

Key Questions

Key questions with respect to impact cratering include (in no particular order) the following:

• How does impact cratering work in diverse planetary environments? What are the pressure and temperature conditions throughout the event, the shock environment, the duration of effects, the excavation and ejection dynamics, and depositional physics? How do these processes vary with the scale of the impactor (ranging from micrometeoroids to asteroids)?

- How is local terrain affected by a major impact event? What is the extent of affected materials? How are materials mixed and redistributed in the process?
- How did the early heavy bombardment influence planetary evolution? For example, did it cause the crustal dichotomy or affect the volatile inventory on Mars? Did it cause the offset between the Moon's center of mass and center of figure? Did it significantly influence the rotations of the planets?
- What effect did the bombardment occurring prior to 3.9 billion years ago have on Earth? Did it influence life? What effects have collisions had, in general, on the evolution of life on Earth?
- What has been the effect of impacts on the evolution of planetary and satellite atmospheres? How did post-accretional bombardment affect the volatile inventories of the terrestrial planets?
- Was Earth's Moon formed by a giant impact of a Mars-size planetesimal? Was the Pluto-Charon binary formed analogously? Were impacts important in stripping surface layers from planets?

Chronology

The actual history of a planet and its dynamic processes are poorly described until the relative ages of identified geological units and epochs are combined with absolute age determinations. Such knowledge of absolute ages is necessary for understanding both the thermal and the internal dynamic evolution of a planet, as well as for ascertaining the historical flux of impactors in the planet's region of space. Surface ages have been estimated from the cratering record (i.e., by crater counts), but only by invoking very uncertain assumptions and extrapolations. In many cases even a rough measurement of the absolute age would constitute great progress (e.g., in defining whether the "recent" volcanics visible on Olympus Mons are a few tens of millions of years old or have existed for more than a billion years). In other cases, such as the cratering flux in the Earth-Moon region over the last 3 billion years, identifying the ages of several specific events (e.g., Copernicus) more precisely to within a few million years is most desirable.

The determination of an absolute age requires that radiogenic isotopes be measured in a silicate rock that was heated, even melted, during the event in question; that is, these determinations can be made only on, for example, a volcanic or metamorphic rock, or an impact melt. Obtaining this type of information, however, is very difficult, because it involves detailed and complex studies of samples; it has been done only for Earth, the Moon, meteorites, and probably Mars (through the SNC meteorites delivered to Earth). Sample return may remain the only viable way of determining chronologies, but it should be emphasized that determination of even relatively imprecise ages can be very valuable in some cases. The flexibility, affordability, and feasibility of achieving many of these goals would be greatly enhanced by development of even crude dating techniques that could be placed aboard landed science packages.

As a major outcome of the exploration of the solar system with spacecraft, impact craters are now recognized in abundance, from the pock-marked surface of Mercury to the heavily bombarded small satellites of Neptune. Characteristics of crater populations, including petrographic, geochemical, isotopic, structural, and stratigraphic features, can provide information on the nature of the impactors, their velocities, and the temporal structure of the impactor population, in turn leading ultimately to definition of their orbits and sources. Interplanetary comparisons of crater populations (e.g., their size-frequency characteristics) are necessary to understand the nature of possible impactor populations.

The lunar highlands, for which the most complete data record is available, show the scars of an intense early bombardment (at least 3.8 billion years old), a declining flux over the period of extant volcanism, and occasional scattered collisions with small impactors during the last few billion years.

In the absence of absolute dates, relative crater counts and stratigraphic principles are the only means of establishing planetary chronologies. Establishing the interplanetary correlation of geologic time in this manner is more difficult.

The cratering records of planets reflect the populations of impactors in the solar system. Because planets are believed to be produced by the accretion of planetesimals, even the earliest crustal history necessarily involved intense bombardment during the latest stages of accretion. This stage is commonly correlated with the early heavy bombardment recognized, for instance, on Mercury. The cratering record is not well characterized, though, and so any interpretation of it is not very secure. In particular, it is not known from observational evidence whether or not the same population is responsible for all the dominant early cratering in the inner solar system. Nevertheless, a single population is generally assumed, and the lunar record is extrapolated to the other terrestrial planets in order to estimate ages. The relationship between the cratering records in the inner solar system and on the outer planets' satellites is more uncertain; hence the chronology of the outer solar system is even less well understood.

The specific nature of impactors (i.e., whether the objects are of cometary or asteroidal or of some other origin) is not usually known from study of the craters themselves, except for a few on Earth and possibly the Moon (and to some extent Ganymede). At present, however, impactors in the inner solar system are mainly perturbed asteroids or comets; more recent impactors on the outer planets' satellites are principally comets and comet-like bodies. For Earth, whether episodes of periodic cratering have occurred over the last few hundred million years is controversial, but present evidence favors a steady, albeit sporadic, bombardment.

On bodies where regoliths develop, the dominant classes of impacting objects leave a chemical signature. Under favorable circumstances this signature can be identified, so that analyses of regolith samples are valuable in this regard. Also, individual fragments in the uppermost region of the regolith acquire a record of irradiation by the solar wind, solar flares, and galactic cosmic rays; analysis of such material can therefore yield measures of the fluxes and/or compositions of those types of radiation, both now and in the past, and can be used to date impacts.

Key Questions

Key questions with respect to chronology include (in no particular order) the following:

- What is the age of the heavy bombardment for Mercury and Mars? Was the population of impactors for the mercurian and martian heavy bombardment the same as that for the Moon?
- What was the nature of the impactors in the lunar heavy bombardment? Did the rate of this bombardment decline continuously from 4.4 billion to 3.8 billion years ago, or was there a distinct population responsible for the late basins?
- What have been the cratering rates on the different terrestrial planets since the end of heavy bombardment? Has the cratering of the inner solar system been approximately steady over the last 3 billion years, or have there been large stochastic fluctuations (e.g., comet showers)?
- What portion of present-day cratering on Earth is derived from comets as opposed to asteroids? What are the mechanisms delivering these bodies?
- What are the origins and flux histories of the crater populations in the outer solar system? What is the relationship between bombardment of the terrestrial planets and bombardment of the satellites of the outer planets?
- Are planetocentric impactor populations responsible for significant cratering on the outer-planet satellites?
- What crater populations are expressed on Pluto and Triton? Can they be used to constrain the mass distribution of material in the Kuiper Belt?

Volatiles

The distribution, history, and behavior of volatiles are major elements in understanding solid planetary objects. The inventory of volatiles currently present on each body provides important clues to the origin and evolution of that body. Furthermore, the history of volatiles is key to understanding interactions with the atmosphere and climate phenomena (see the section "Planetary Atmospheres" in this chapter). Finally, the types of volatiles present and their distribution frequently determine the nature of volcanic and tectonic modification of surfaces.

In addressing this topic, it is valuable to recall that, depending on heliocentric distance, the materials that are considered "volatile" vary greatly; for example, water is volatile throughout most of the inner solar system, but is an involatile "rock" on most of the bodies in the outer solar system.

The surfaces and atmospheres of solid bodies interact physically and chemically. A record of this interaction may be preserved in landforms and in the chemistry of the surface materials. Moreover this interaction may be observed directly as atmospheric constituents condense on the surface or transport materials across the surface. The solid bodies are also major sources of the atmospheres themselves. The degree of interaction ranges widely, from being almost negligible, as on the Moon and many of the icy satellites of the outer planets, to substantial, as on Earth. Knowledge of atmospheric-surface reactions also ranges widely. While many interactions on Earth and Mars are reasonably well understood, weathering on Venus, eruptions on Io and Triton (and possibly Titan and Pluto), and the nature of condensates on many of the icy satellites are very poorly understood.

Key Questions

Key questions with respect to volatiles on various bodies include (in no particular order) the following:

- What are the erosional and sedimentation histories of different planetary bodies, particularly Venus and Mars? To what extent have materials been redistributed across their surfaces? What are the processes whereby this redistribution has taken place?
- What are the extent and nature of aeolian and sedimentary deposits on Titan, Triton, and Pluto?
- What role do volatiles play in climate change? Specifically, what do the erosional histories of Venus and Mars imply for climate change?
- What is the extent of nonwater volatiles in outer solar system objects, both as indicators of nebular formation conditions and as critical elements affecting tectonic, volcanic, and atmospheric processes?
- What role do carbon and organic materials play throughout the solar system? What is the relationship of these materials to primitive objects and to the chemistry of life?
- What is the nature of current volatile activity on Mercury and the Moon? Are the radar-reflective materials that are concentrated at Mercury's poles made of water ice or some other volatile trapped in craters? Is this material endogenous or brought in by volatile-rich (possibly cometary) impactors? Do similar deposits exist at the lunar poles?
- How do volatiles determine the character of volcanism on various bodies? What role do water and sulfur play on different bodies?
- What are the volatile inventories of the terrestrial planets, and why do they differ? What do the distinct volatile inventories imply for accretion, differentiation, and the states of the planets as accretion ended?

OBJECTIVES

This section outlines the major objectives for study of each of the aspects of solid bodies described above and indicates the highest-priority investigations required to meet these objectives.

Internal Structure and Dynamics

Determine the internal structure and dynamics of at least one major planetary body other than Earth or the Moon. This knowledge is fundamental for understanding any planetary body, but within the time frame covered by this report, the greatest progress will come from removing the uncertainty that masks the interiors of all planets other than Earth and the Moon (which have been probed seismically). Of high priority are analyses of planetary bodies whose mantles are most likely to be vigorously convecting, and thus most similar to Earth's.

Planetary Magnetism

Achieve a better understanding of the generation of magnetic fields. For a given planet, orbiter studies to characterize the static and time-varying main field and determination of the precession rate of the planet's spin axis to estimate the moment of inertia would contribute to the understanding of the present state of the interior and possible core, and its relationship to magnetic field generation. Measurements of possible remanent magnetization of surface units for a rocky world might reveal significant variations of the field throughout the planet's evolution. Seismic observations and geodetic measurements would yield information on the structure of the core and the nature of core-mantle coupling.

Tectonics

Relate surface tectonic features to the evolution of planetary stress fields, and use tectonic features to probe lithospheric structure and mantle-lithosphere mechanical interactions. The global characterization of tectonics requires imaging and topographic coverage at a resolution commensurate with the length scales of the features.

Formation and Evolution of Primary Crusts

Characterize the surface chemistry of major satellites in the outer solar system and of Pluto. This would constitute an important step in understanding the evolution and internal structures of these worlds.

Volcanism and Mantle Evolution

Advance significantly our understanding of the crust-mantle structure, the geochemistry of surface units, morphological and stratigraphic relationships, and geochronological calibrations for any solid planet. Understanding of such features is critical to developing a clearer picture of planetary evolution.

Impact Cratering

Develop the necessary theoretical and experimental basis for understanding the physics of cratering in all regimes. This will require improved numerical techniques and study of the behavior of a range of materials under conditions of high temperature and pressure.

Volatiles

Determine the inventory and history of volatiles and surface-atmosphere interactions on Mars, Pluto, and Triton. These provide important information about a planet's or satellite's origin and evolution. Volatiles reside in the atmosphere and on the surfaces (in some cases as condensed fluids such as water bodies) and are expelled from interiors by degassing or from magmatic activity. Obtaining basic information about the abundances and types of volatiles on all planets, even those lacking significant atmospheres, such as the Moon and Mercury, provides knowledge of their evolution.

Chronology

Establish the chronology of at least one major planet or satellite in the solar system besides Earth and the Moon. Relative and absolute chronologies of craters allow some calibration of the evolution of planetary surfaces in a stratigraphic manner (e.g., through the study of magmatic and sedimentary sequences). Data on relative cratering densities have assisted in understanding the evolution of the surfaces of the terrestrial planets and the icy and rocky small bodies of the outer solar system. Only for the Moon and Earth, however, are there relevant geochronological data, and the terrestrial record is statistically reliable back for, at best, only a few hundred million years, even for large craters.

WHAT TO STUDY AND WHERE TO GO

Mars

At present, the scientific issues and questions concerning Mars make it the preeminent candidate among the solid planets and satellites for further study.

This is especially true because of the unfortunate loss of Mars Observer. The structure and evolution of the martian interior are of direct relevance to comprehending Earth. Understanding of martian internal structure and dynamics can be gained from seismic information, from analysis of high-quality, globally distributed gravity and topography measurements, from determination of the moment of inertia, and from geodetic measurements derived from surface stations designed to measure rotational fluctuations. These latter measurements would yield information on the structure of the core and the nature of core-mantle coupling. While challenging to obtain, such measurements would be highly valuable.

Mars Observer would have provided gravity and topography information of the required accuracy to elucidate the mantle's temperature structure. This information remains to be acquired. COMPLEX also supports the acquisition of seismic information pertinent to the martian interior. The deployment of a network of eight or more seismic stations as part of an international Mars geophysical network, currently under discussion, would accomplish this goal. Although Mars has a very weak magnetic field at best, measurements of possible remanent magnetization of surface rock units could constrain the history of the ancient martian field, which is predicted to have been relatively strong.

An outstanding question for tectonics is the origin of the Tharsis rise, exploration of which will require the application of stress models constrained by gravity and topography and information on the temporal and spatial nature of the global stress field obtained from observations of surface tectonics. In terms of crust and mantle evolution, Mars is a planet—intermediate in size between Earth and the Moon—for which a stratigraphic history, with clear global changes over time, has been derived. Mars is thus a prime target for more detailed study. The (probable) Mars-derived SNC meteorites are also significant in providing a context for such study. A knowledge of the essential crust-mantle structure, that is, the thickness of the martian crust and some idea of its regional variation (from seismic measurements), is an important factor. Global and in situ chemical and mineralogical measurements—and ultimately, selected returned samples—would provide the geochemical, mineralogical, isotopic, and chronological information necessary to outline the evolution of Mars and make comparison with Earth and the Moon more fruitful.

The chronology of Mars, if clarified with some absolute ages determined on returned samples of selected rock units, is of great importance in understanding the flux and source of impactors in the inner solar system over the last few billion years. Thus the retrieval of datable samples from identifiable stratigraphic units from Mars is of high priority in cratering flux studies. However, unraveling the structure of an early heavy bombardment history of Mars will probably require more detailed future geological study (including determination of ages), because of the complicated ancient history of Mars.

Mars appears to have had a complex evolution in which volatiles appear to have played an important role. For example, valley networks and large channels incised into the surface strongly suggest erosion by water at times in the past. The presence of water ice beneath the seasonal dry ice cap at the north pole has been confirmed. The characteristics of the volatiles have a considerable influence on the possibilities for life. An improvement in our understanding of the present inventory of volatiles in both Mars's atmosphere and its surface materials, including isotopic measurements, is necessary for understanding the evolution of Mars. Surface materials that are important targets for analysis include the soil (with depth profiles), volcanic rocks, impact ejecta, and the polar ices. Many important measurements of surface materials must necessarily be made in situ. Monitoring of the volatiles as they are currently cycled in atmosphere-surface activity continues to be an important objective in the study of Mars.

Pluto and Triton

Outside of the jovian and saturnian systems, Pluto and Triton are the solid bodies in the outer solar system that have the highest priority for exploration. These bodies represent a new class of solar system objects in terms of size and composition and would be best studied synergistically. Determinations of their volatile reservoirs may provide fundamental constraints on their origins and thus on large rock-ice planetesimals in the neptunian formation zone and somewhat beyond. Triton—and probably Pluto also—has a complicated surface-atmosphere exchange regime that is potentially of relevance to comparisons with Mars. Pluto is also unique in the degree to which its atmosphere responds to solar forcing. In addition, there may be an exchange of mass between Pluto and Charon.

Missing is information on the composition and location of the ices on Pluto and Triton and on their relationships to tectonic and volcanic evolution (including the tidal heating and melting hypothesis for Triton), to volatile movement and climate change, and to (nonbiological) evolution of organic matter in the solar system. Differing compositions and geological evolutions of Pluto and Charon may provide fundamental constraints on the origin of this binary system (e.g., by an impact of two precursor objects).

Understanding of cratering on icy worlds and of the bombardment history of the outer solar system will be greatly advanced by successful completion of the Galileo and Cassini missions. Key information on bombardment fluxes can also be obtained from worlds at the edge of the solar system: Pluto and Triton. Only a portion of Triton's surface has been imaged. An understanding of Triton's global cratering history would be invaluable for understanding the satellite's geological evolution. Characteristics of the crater population could then be related to the impactor populations in this region, dominated by Kuiper Belt and related objects. Because of possible confusion from neptunocentric debris, however, Pluto and Charon make even better counting surfaces: craters on these objects should be relatively smaller because of lower impact velocities, Pluto and Charon undoubtedly have surfaces of greatly differing geologic age, and the pair travel along their mutual orbit through the probable inner region of the Kuiper Belt.

Between Pluto and Triton, Pluto has the higher priority. First, Pluto has not yet been visited by spacecraft, and second and most important, it is a time-critical target, since it has passed perihelion and is beginning to retreat from the Sun. It will become increasingly more difficult to reach, and as it retreats, a growing portion of its surface will not be illuminated due to its high obliquity (122.5°), and its surface will cool, causing its nitrogen atmosphere to freeze.

Mercury

Given the increasingly detailed studies of Mars and Venus, plus the knowledge gained by previous lunar exploration, Mercury stands out among the terrestrial planets as the least understood, although it is a planet rich in potential scientific reward.

A major increase in understanding of planetary magnetic-field generation would be gained from analysis at Mercury, the only other planet whose magnetic field is likely generated due to convective motions in an iron core, much as Earth's magnetic field is. The time-varying and static components of Mercury's main field should be determined. Measurements of possible remanent magnetization of mercurian surface units could constrain the evolution of Mercury's field.

A first-order characterization of the surface chemistry of Mercury, even locally, would constitute an important step in understanding the evolution of this planet and of the innermost region of the solar system. Some surface features are widely accepted as volcanic (and volcanism is a crust-forming process), but we have little firm information on what kind (or kinds) of volcanic rock may exist, or whether such rock is different from older terrains. Indeed, we do not know if Mercury has a significant crust that is distinct from a mantle. The large core of Mercury suggests a unique history in which the planet's original mantle and crust may have been stripped off by some mechanism such as catastrophic impact. Surface chemical information obtained by orbiting or flyby spacecraft would go a long way toward elucidating Mercury's history.

Imaging at resolutions and with coverage greater than those obtained by Mariner 10 would provide better evidence of the nature of the materials (and hence the processes) that were part of Mercury's evolution. Far more ambitious, but ultimately necessary, are seismic determinations of the crust-mantle structure and the acquisition of samples for geochemical and geochronological analysis; it is unfortunate that sample retrieval from Mercury is so difficult to achieve.

Mercury has been imaged at low resolution and over only about 45% of its surface. Thus even its relative stratigraphy and crater density are poorly known.

Global imaging at resolutions of less than 1 km is required to provide adequate data for reliably comparing the crater populations of Mercury and the Moon and thus having a basis for understanding whether the impactor populations responsible for ancient cratering on these two bodies were the same or different. The same high-resolution imaging is required to assess the temporal changes in cratering on Mercury and to provide a more detailed picture of its geological evolution through the use of crater density as a determinant of relative age. Thus global, high-resolution imaging of Mercury is a priority. The retrieval of samples from Mercury and calibration of the planet's evolutionary stages with absolute chronology would be most helpful in understanding the most ancient heavy cratering in the inner solar system.

Moon

We have a first-order understanding of the nature and chronology of the Moon's crust and mantle evolution, derived mainly from returned Apollo and Luna samples. However, the geologic context of these samples is only locally known, and it is clear from incomplete remote-sensing data that the samples do not represent the variety of lithologies constituting the lunar crust (both primary and secondary). Without a more thorough evaluation of Earth's nearest neighbor, theories of the origin and early evolution of the Earth-Moon system remain poorly constrained. A detailed assessment from orbit of the Moon's composition and geology on a global and regional scale is thus the next essential step to understanding the evolution of this small end-member of the silicate (terrestrial) planetary bodies. Comparisons with other planets, including Earth, would then be much more definitive. Ultimately, improved seismic studies and acquisition of surface chemistry, including isotopic measurements, from selected locations will be needed to adequately understand lunar evolution.

The Moon provides a unique and relatively accessible window into solar system history at 1 AU. Much can also be learned about impact processes from the synoptic view afforded by analyses from lunar orbit. Because the lunar surface remains largely unaltered by weathering, the Moon is a natural laboratory for studies of impact basins and craters and for investigations of the character and scale of materials shocked, melted, and mixed with surrounding lithologies.

The Moon has become the cornerstone for absolute chronology of the cratering in the inner solar system because it has cratered surfaces dating back at least 3.9 billion years and because samples have provided absolute ages. However, this record is not known in much detail, yet it is particularly important because the Moon certainly records the population of impactors that affected Earth. Thus establishing the ages of particular craters in the last few billion years to calibrate the record of relative crater density is necessary to properly understand the influence of cratering on Earth's history. We already know enough about this more recent record to be convinced that the bombardment is of heliocentric origin and from a population that affected the entire inner solar system. If this lunar record is established in sufficient detail, then possible periodicities could be detected.

The ancient intense cratering is somewhat different, at least insofar as it created large basins, and the ancient impactors had compositions possibly distinct from those of the more recent impactors. The temporal evolution of this ancient bombardment and the source of the impactors are poorly constrained at present, and geochronological information from selected impact basins is of high priority in understanding this ancient bombardment and in assessing the source of the impactors. Returned samples or sophisticated in situ geochronological methods (which so far have not been developed) are of high priority in establishing the cratering record in the Earth-Moon system.

Analysis of evidence of the flux and composition of solar wind and solar flares—present and past—preserved in lunar regolith has yielded novel insights into the long-term evolution of the Sun. Future studies could make useful progress in this area by utilizing specific lunar surface samples carefully selected on the basis of well-defined exposure ages.

Outer Planet Satellites

In the outer solar system, the nature and sources of stress responsible for global tectonics on Europa, Ganymede, Enceladus, Ariel, Miranda, Triton, and possibly Titan and Pluto are compelling issues. The post-Galileo and post-Cassini focus could potentially be Io, Europa, and Titan, the former two because of their individually unique, tidally driven natures, the latter because it may be the most continually active, volatile-rich icy satellite.

Attempts to recover gravitational moments (e.g., J_2) for these satellites from the tracking of orbiting spacecraft or from multiple flybys could also have great value in the fundamental determination of internal mass distributions. Better characterization of icy satellite surface chemistry would constitute an important step in understanding the evolutions and internal structures of these worlds. This gravitational and chemical information should be provided for the jovian and saturnian satellite systems by Galileo and Cassini, respectively.

Outer Planets

In the longer term, global characterization of the magnetic fields of the outer planets would provide insight into the nature of planetary magnetic field generation.

Venus

A central question about Venus is the nature of its lithosphere-mantle coupling. This can be addressed by reconciling models of mantle flow and their associated surface stress fields with detailed observations of surface deformation, along with modeling of Magellan-derived gravity measurements. Further progress requires seismic, global, or local chemistry, and possibly heat-flow information. While Venus is likely the most seismically active terrestrial planet other than Earth, deployment of a seismic network that would survive for the period required to perform an adequate survey would be severely complicated by the planet's high surface temperature and pressure.

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PLANETARY ATMOSPHERES

The gaseous envelopes that surround various solar system objects show remarkable diversity. Venus, for example, has a massive CO_2 atmosphere with a general circulation that is dominated by global spin. Its neighbor, Earth, has an N_2 atmosphere that is only 1% as massive as Venus's and a general circulation that consists of mid-latitude jets and large-scale eddies. Mars also has a CO_2 atmosphere, but its surface pressure is only about 0.7% that of Earth, and it migrates from pole to pole with the seasonal cycle. Jupiter's predominantly H_2 atmosphere contains a large storm that has been raging for several hundred years, and wind speeds of up to 400 m/s have been observed on Saturn and Neptune. It is suspected that Pluto's atmosphere largely freezes out when the planet recedes from the Sun in its highly elliptical orbit.

This diversity of atmospheric properties is related both to variations in initial conditions during formation in the protosolar system disk and to different physical circumstances under which the atmospheres have subsequently evolved. Planetary masses, for example, span five orders of magnitude, and effective solar heating rates vary from 10.6 (Earth's equals 1) for Mercury when it is at perihelion, to 0.0004 for Pluto when it is at aphelion. Planetary atmospheres also display an equally wide range of physical processes—such as winds, storms, lightning, aurorae, dust devils, and transport of frozen volatiles between polar caps. Careful measurements, theoretical modeling, and comparison of processes on different bodies provide rich opportunities for scientific insight. Only in the last decade or two, however, has our knowledge of nonterrestrial atmospheres become complete enough to allow this comparative study. The results have proven to be both interesting and scientifically rewarding.[13]

This discussion of planetary atmospheres, which begins with a brief outline of the types of atmospheres found in the solar system and continues with a summary of what is currently known about them, reflects a comparative approach and is organized according to four scientific themes:

1. Composition and chemistry,
2. Dynamics and thermal structure,
3. Climate change, and
4. Origins and evolution.

In some cases there is overlap and the separation is artificial, but these themes nevertheless provide a framework for classifying the behaviors of the different atmospheres and for highlighting the key questions remaining to be answered. The discussion of themes continues with a description of objectives in each of the thematic areas that need to be addressed to further studies of planetary atmospheres. The final section, "What to Study and Where to Go," identifies the most important studies to be performed and the planetary bodies to be investigated to enhance our understanding of planetary atmospheres.

DESCRIPTION OF ATMOSPHERES

The properties of solar system atmospheres are summarized in Table 4.2, which groups the atmospheres according to their chemical composition. The H_2-He atmospheres of the giant planets reflect the chemical composition of the Sun, since the gravitational fields of these planets are strong enough to have prevented the escape of H_2 from the time of their formation within a common solar nebula. The next category contains the predominantly CO_2 atmospheres of Venus and Mars, followed by the dense N_2 atmospheres of Earth and Titan. Venus, Earth, and Mars, in spite of their close proximity, have had very different histories. Venus is desiccated; Earth has abundant water in its atmosphere-ocean system; and Mars, while showing evidence of ancient fluvial activity, is currently too cold for water to exist as a liquid on the surface. Clearly, climate sensitivity and the history of volatile compounds that can shift from surface to atmosphere or can escape to space are important comparative issues for these planets.

The next category is the less dense N_2 atmospheres of Pluto and Triton, whose major constituent is in vapor-pressure equilibrium with surface frost. The SO_2 atmosphere of Io arises from volcano-like geysers that are driven by tidal heating of Io's interior by Jupiter. The tenuous, collisionless, Na atmospheres (actually exospheres) of Mercury and the Moon are maintained in equilibrium between escape and resupply, probably by sputtering of Na from their surfaces through the impact of charged particles in the solar wind. The remaining atmospheres (known as comae) are the freely escaping ones of Chiron and other comets.

Atmospheres affect the planetary surfaces they envelop. They filter harsh ultraviolet and particle radiation streaming in from the space environment, thus preventing the destruction of the more fragile molecules—some of which are necessary for biological processes. Atmospheres can protect surfaces from erosion caused by impacts of cosmic dust and small asteroids, yet they contribute to surface erosion caused by transporting planetary dust at high speeds, and—in the case of Earth—raising water vapor to high altitudes where it condenses and erodes the surface as it flows to lower levels. Furthermore, volatiles are transported over the surface of a body through the sublimation of frost from warmer surface areas and its redeposition at colder areas—a process that can equalize the atmospheric temperature around the body. The atmospheres of Jupiter, Saturn, and Neptune transfer heat from their interiors to the level of emission to space.

SCIENTIFIC THEMES

Composition and Chemistry

Planetary atmospheres can be divided into broad classes according to their chemical compositions. The major categories are the H_2-He atmospheres of the giant planets, the terrestrial CO_2 atmospheres, and the N_2 atmospheres of Earth, Pluto, and the satellites Titan and Triton.

TABLE 4.2 General Properties of the Atmospheres Around Solar System Objects

Classes of Atmospheres	Solar System Object	Composition—Main Components	P, T[a] at Base or Visible Cloud and T in Thermosphere	Nature of Upper Cloud Deck	Typical Flow Speed	Typical Temperature Contrasts
H_2-He atmospheres of the giant planets	Jupiter	H_2, He, CH_4, NH_3^b . . .	0.5 bar, 150 K, 1000 K	NH_3	100 m/s	5 K
	Saturn	H_2, He, CH_4, NH_3^b . . .	1 bar, 160 K, 400 K	NH_3	400 m/s	5 K
	Uranus	H_2, He, CH_4^b, . . .	1 bar, 80 K, 870 K	CH_4	200 m/s	2 K
	Neptune	H_2, He, CH_4^b, . . .	1 bar, 80 K, 600 K	CH_4	400 m/s	2 K
Terrestial CO_2 atmospheres	Venus	CO_2, N_2, SO_2^b, $H_2SO_4^b$ . . .	90 bar, 730 K, 200 K	H_2SO_4	100 m/s	5 K
	Mars	CO_2^b, N_2, H_2O^b, . . .	7 mbar, 200 K, 400 K	H_2O	40 m/s	40 K
N_2 atmospheres	Titan	N_2^b, CH_4^b, . . .	1.5 bar, 90 K, 180 K	CH_4	?	5 K
	Earth	N_2, O_2, Ar, H_2O^b, . . .	1 bar, 280 K, 1000 K	H_2O	20 m/s	40 K
	Pluto	N_2^b, CO^b, CH_4^b, . . .	3-600 μbar?, 35-45 K?, ?	N_2	?	<20 K
	Triton	N_2^b, CO^b, CH_4^b, . . .	14 μbar, 38 K, 100 K	N_2	?	?
Volcanic	Io	SO_2^b	0.1-10 nbar,[c] 120 K, 600 K	SO_2	200 m/s	?
Exospheres	Moon	Na, K, . . .	?	—	?	—
	Mercury	Na, K, . . .	?	—	?	—
Unknown	Charon	?	?	?	?	?
Comae	Comets	H_2O, CH_4, CO, CO_2, CH_3OH	—	—	—	—
	Chiron	CO?, ?	?	?	?	?

[a]P, pressure; T, temperature.
[b]A condensing, time-variable constituent.
[c]Time variable.

H_2-He Atmospheres of the Giant Planets

Data from the Voyager 1 and 2 missions and ground-based measurements reveal that the atmospheres of the giant planets are predominantly molecular hydrogen (~85 to 95% by number), with the remaining component being mostly helium. On Jupiter and Saturn the CH_4 and NH_3 mixing ratios suggest enhancements in the C/H and N/H ratios by at least a factor of three over the solar abundances that one might expect if these planets were formed directly from condensation of the solar nebula. On Uranus and Neptune, the CH_4 mixing ratios are larger by at least a factor of 30, clearly indicating an origin other than directly from the solar nebula, but the NH_3 mixing ratios are only 0.1 times the solar value.[14] To first order on Jupiter and Saturn one expects from thermochemical considerations, and observations confirm, that saturated hydrides of reactive atoms (e.g., H_2O, PH_3, and GeH_4) occur at roughly solar abundances; surprisingly, H_2S is not detected, nor is its likely condensate, NH_4SH. In these atmospheres trace chemical species, such as C_2H_6, C_2H_2, HCN, CO, and N_2, may have either a thermochemical origin deep in the interior—from which they are convected upward to the visible atmosphere, thus becoming indicative of vertical heat transport—or a photochemical origin. Our current understanding is that C_2H_6 and C_2H_2 have a photochemical origin, whereas N_2 (undetected) is probably of thermochemical origin. The species HCN and CO have both photochemical and thermochemical origins, with "photochemical" oxygen for the latter species probably supplied by the infall of meteoroids or derived from rings and satellites. Measurement techniques used to date are not able to unequivocally differentiate the relative importance of these two sources.

Haze is ubiquitous in the tropopause regions of the giant planets and is partly of photochemical origin: condensed N_2H_4 from NH_3 photochemistry on Jupiter, condensed P_2H_4 from PH_3 photochemistry on Saturn, and condensed C_2H_2, C_2H_6, and C_4H_2 from CH_4 photochemistry on Uranus and Neptune. The stratospheric methane balance is particularly perplexing on Neptune, where observations indicate a high concentration in spite of a cold tropopause temperature. Generally, high-molecular-weight compounds are not of first-order interest in the giant planets, but the jovian polar stratosphere is the exception. The detection of heavier compounds and the existence of a distinct stratospheric haze in the polar regions suggest efficient paths for making complex molecules under conditions of reduced destruction by solar photolysis. Jupiter's high-latitude haze is presumably of auroral origin, but its composition is unknown.

Terrestrial CO_2 Atmospheres

The terrestrial planets Venus and Mars can be classified as having buffered CO_2 atmospheres. The present Earth does not have a CO_2 atmosphere but would have one if life did not exist and if the surface temperature were elevated to liberate CO_2 from carbonate rock and evaporate the oceans. In fact, the N_2/CO_2 inventory ratios are comparable for these planets. Venus and Earth (if the CO_2 in limestone is included) have comparable absolute abundances of CO_2. The martian atmosphere is buffered by the permanent CO_2 polar cap in the south. The northern polar cap is composed of water ice. Earth and Mars have large surface reservoirs of water, whereas Venus is devoid of water. Unlike Mars, Triton, and Pluto, which have polar caps, Earth's ice caps are not composed of the major atmospheric constituent.

The stability of these CO_2 atmospheres in the presence of geologically fast destruction rates by solar photolysis is difficult to explain. It has been hypothesized (but not yet demonstrated) that this stability is due to fast catalytic cycles involving HO_x (odd hydrogen: e.g., H, OH, HO_2, and so on) compounds derived from H_2 on Venus and H_2O (wet phase) and H_2 (dry phase) on Mars. During the dry phase on Mars, O_3 plays a critical role as the principal source of the excited atomic oxygen, $O(^1D)$, which oxidizes H_2 to form odd hydrogen. Ozone is also an important diagnostic species of photochemical processes. In the case of Mars, homogeneous chemistry may not be sufficient to maintain the stability of CO_2; accordingly, heterogeneous chemistry involving dust storm particles has been proposed. On Venus the catalytic cycle is probably initiated by photolysis of HCl and may involve sulfur compounds.

The high surface pressure and temperature on Venus establish a chemical region in the lowest 10 km where thermochemical equilibrium processes are more important than photochemistry. This may explain why the halogen elements, which are normally lithophilic, have exceptionally large abundances in atmospheric compounds, for example, HCl and HF. Similar remarks apply to the element sulfur. Active volcanism on the planet may augment the supply of these elements. Several lines of evidence suggest that the present thin atmosphere of Mars is only a remnant of the total outgassing that has taken place since planetary formation. Some of this evidence has been provided by comprehensive in situ measurements of atmospheric chemical and isotopic composition (made by the Viking landers) and, more recently, by telescopic determination of the atmospheric D/H ratio. In spite of the excellent quality of these data, their interpretation in terms of production and loss mechanisms is far from complete for a variety of reasons, including uncertainties about how often the martian atmosphere may have been subject to massive exogenic events (cometary and asteroidal impacts). Other critical uncertainties relate to the processes leading to atmospheric loss from the thermosphere as well as the chemical and physical processes that couple the atmosphere and surface. The location of the sources of the outgassed products is not known and may include carbonate and nitrate rocks, adsorbed water and carbon dioxide, polar ice, permafrost, or even aquifers. Water and carbon dioxide reservoirs in thermal equilibrium with the atmosphere—polar caps and adsorbed gases—are elements in an incompletely understood, possibly time-varying system.

N_2 Atmospheres

The other broad category of atmospheres is N_2 atmospheres, which envelope Earth, Titan, Triton, and Pluto. Earth's 1-bar atmosphere, predominantly N_2, has been profoundly influenced by the evolution and presence of life, because living organisms control the 20% O_2 content and maintain Earth's atmosphere substantially away from thermochemical equilibrium. Terrestrial oceans modify Earth's atmospheric chemistry by supplying the most important greenhouse gas, H_2O, and the most important oxidizing agent, the radical OH. Photochemistry of O_2 yields O_3, which absorbs solar radiation to create the thermal inversion in the stratosphere and also shields life from harmful ultraviolet radiation. Carbon dioxide, most of which has been removed from the atmosphere to form carbonates, is still the second most important greenhouse gas and may have contributed substantially to the evolution of the atmosphere.

Triton's atmosphere is also largely buffered by interaction with the satellite's surface. The atmospheric surface pressure (~14 microbars) and temperature (~38 K) are intimately tied to the temperatures of N_2, CO, and CH_4 frosts and to the albedos of the surface frosts and materials. Pluto, similar to Triton in size and mass, also has a high albedo, indicating active resurfacing with frost, and has a similar near-infrared frost spectrum that implies Pluto probably has an N_2, CO, and CH_4 atmosphere. Yet Pluto has a scale height at the microbar level that is 2.5 times that of Triton—presumably due to a greater abundance of CH_4 in Pluto's atmosphere that heats it through absorption of solar radiation. Voyager images of Triton revealed a polar cap and an overall albedo pattern that resembles crude albedo maps of Pluto, including polar caps, that are derived from recent observations of mutual occultations and eclipses with its satellite Charon. It is not known whether isolated frost deposits exist outside the polar regions on either body.

The photochemistry of CH_4 in these atmospheres leads to the formation of C_2H_4 and C_2H_2, which are known to condense and form a thin photochemical haze in the lowest 30 km of Triton's atmosphere, and to the production of H and H_2, which are transported upward to the ionosphere. Nitrogen and carbon monoxide photochemistry leads to the formation of an ionosphere and N atoms. The relatively weak gravitational fields of Pluto and Triton allow significant thermal escape of N, H, and H_2 from their exobases. Escape of these species from Triton is the dominant source of mass for Neptune's magnetosphere; moreover the precipitation of energetic magnetospheric electrons may constitute two-thirds of the power input to Triton's upper atmosphere.

In contrast with Triton's thin atmosphere, Titan's atmosphere is the most massive N_2 atmosphere in the solar system at ~1.5 bar and has a composition similar to that of the primitive, mildly reducing atmosphere that Earth may have once possessed. With a CH_4 mixing ratio of a few percent, the combined photochemistry of N_2 and CH_4 leads to the formation of a large suite of hydrocarbons, organic molecules, and nitriles that condense to generate an optically thick photochemical smog that envelops the entire satellite and raises the optical limb 250 km above the surface. This haze functions as ozone does on Earth to absorb solar radiation and heat Titan's stratosphere to about 100 K above the tropopause temperature. Sedimentation of the haze particles to the surface over geological times scales could have led to the accumulation of more than 200 m of liquid and solid hydrocarbons on the surface; however, radar observations are not consistent with a simple liquid surface layer. The photochemical destruction of CH_4 proceeds efficiently because H and H_2 escape thermally from the atmosphere at the rate that CH_4 photolysis produces these species, ensuring the irreversible conversion of CH_4 supplied from the interior to less saturated hydrocarbons that alter the surface composition of Titan.

Instruments on the Huygens probe, to be delivered by the Cassini orbiter, are designed to investigate many aspects of the fascinating organic chemistry occurring in Titan's atmosphere. The chemical composition of inert and noble gases, low-molecular-weight hydrocarbons and nitriles, and high-molecular-weight organic material primarily as solid particles will be analyzed by a gas chromatograph/mass spectrometer and aerosol collector and pyrolyzer experiments. A surface science package will determine the state and composition of the surface and may resolve the nature of the photochemical products on the surface. Remote-sensing measurements by the Cassini orbiter will yield complementary information on the spatial distribution of many chemical species. The ion-neutral mass spectrometer will measure the composition above 1000 km, where nitrogen photochemistry and nitrile formation occur.

Oxygen is supplied to Titan's atmosphere by either meteoroidal infall or initial outgassing of CO from a CH_4 clathrate; in either case the dominant chemical form of oxygen is CO. In the outgassing scenario a CH_4 clathrate could also be the major source of the N_2 and Ar components of the atmosphere. The Ar mixing ratio, for which only an upper limit of 0.10 exists, may be the key to understanding the origin of Titan's N_2 atmosphere and is a key objective of the Cassini mission.

Volcanic Atmospheres

The previously discussed categories of atmospheres pose many unanswered questions that can be approached through comparative studies. In contrast, in a class by itself is Io, with a day-side SO_2 atmosphere (of about 0.1 nanobar) that collapses to an exosphere at night and a polar cap of SO_2 frost. It is not certain whether there is a permanent, global atmospheric component in addition to the SO_2 sublimation atmosphere and the local enhanced buffered atmosphere near volcanic sites. Even more uncertain is the vertical and horizontal temperature structure. Yet one can be confident that Io's atmosphere supplies copious amounts of oxygen, sodium, and sulfur atoms and molecules to the inner jovian magnetosphere. Bombardment of Io's upper atmosphere and corona by the plasma in Io's torus may sputter material from both the atmosphere and the surface, heat the atmosphere, and energize the plasma by charge exchange reactions.

Exospheres

Mercury and the Moon have tenuous Na coronas and/or exospheres, and recent radar returns suggest that Mercury may have subsurface polar ice caps. Atoms above the surface on these objects are in ballistic orbits, with negligible mutual collisions.

Atmosphere-Surface Frost Interactions

Atmosphere-surface interactions are particularly significant for Mars, Triton, and Pluto, where the major atmospheric constituents are in vapor-pressure equilibrium with surface frosts. The latent heat of the condensation-sublimation between gas and solid phases should cause the lower atmosphere of Triton and Pluto to be at a nearly constant temperature, and damp the thermal response to changing insolation. Data from the Mariner 9 and Viking missions show that the martian surface pressure experiences a seasonal cycle, driven mainly by radiative processes but also affected by the large-scale circulation, particularly during major dust storms. The presence of surface H_2O ice on Mars is indicated by the high summertime temperature of the northern permanent polar cap, by the observed change in column water abundances with latitude and season, and, less directly, by the detection of seasonal frost in areas shaded by rocks, as observed by the Viking landers.

Frosts associated with gases that have short photolytic time constants on a geological time scale require continuous replenishment from surface and subsurface reservoirs of volatiles. The CH_4 on Titan, Triton, and Pluto is in this category because of its irreversible conversion to more complex, less saturated hydrocarbons that subsequently condense to form hazes. These hazes precipitate and add additional components to surface frosts. Voyager images do reveal intriguing plumes of dark material rising several kilometers into Triton's atmosphere; these may represent modified surface frost material, but their source and the expulsion mechanism are not well understood.

Key Questions

There are many important studies related to the composition and chemistry of planetary atmospheres. Key among these are (in no particular order) the following:

- What are the CO and CH_4 mixing ratios in the atmospheres of Pluto and Triton and what do they imply about the thermal structure, atmosphere-surface interactions, and cosmochemical origins of their atmospheres? To be useful, these mixing ratios must be measured to an accuracy of 100 parts per million (ppm) (since CO and CH_4 dominate atmospheric cooling and heating), and the mixing ratios of other constituents should be measured with an accuracy of 10,000 ppm. What keeps Pluto from being essentially a Triton analog in its albedo patterns, polar cap variations, inventory of volatiles, and other characteristics?

- If irreversible photochemical destruction leads to the formation of more complex hydrocarbons such as C_2H_6, C_2H_4, and C_2H_2, why are their signatures absent in surface near-infrared reflection spectra on Triton and Pluto and not consistent with radar measurements of Titan?
- On the giant planets, what are the N_2 and CO mixing ratio profiles and what do they imply about the relative importance of photochemistry to thermochemistry and convection or vertical mixing in the chemical composition and dynamics of their tropospheres?
- In what form and where does elusive sulfur reside on the giant planets?
- What is the composition of Jupiter's polar haze, and what are the chemical precursors and their connection with the intense auroral bombardment of the polar regions?
- How oversaturated is CH_4 in the neptunian stratosphere relative to the vapor pressure equilibrium at its tropopause temperature, and what are the implications for troposphere-stratosphere air exchange?
- Does Io have atmospheric components in addition to SO_2?
- Why is Venus's atmosphere in a high oxidation state in the photochemical region when O_2 has never been detected? What are the precise mixing ratios of H_2 and O_2 and the distribution of sulfur and halogen compounds? What are the chemical cycles that control these distributions of sulfur and halogen constituents, and what is the role of atmospheric circulation?
- What is the inventory of volatiles on Mars?
- What is the role of homogeneous versus heterogeneous chemistry in the stability of the martian CO_2 atmosphere?
- What are the processes responsible for the escape of the present martian atmosphere, and what inferences can be made about their importance over past climatological epochs?

Dynamics and Thermal Structure

Motions, temperature structure, hazes, and clouds are interdependent in an atmosphere. For planets with solid surfaces, insolation is usually the fundamental forcing mechanism for dynamics, but the location and strength of solar heating are affected by the distribution of clouds that are in turn established by the atmospheric flow field. Thermal radiation exchange and cooling to space are also often modulated by clouds or aerosols. The temperature field is determined by competing influences of radiation and dynamics, with dynamics acting generally toward reducing horizontal temperature contrasts that are being forced by radiation.

The first description of atmospheric structure is traditionally in terms of a global mean vertical temperature profile. As a conceptual tool, a global mean radiative-convective equilibrium can be calculated and compared with the observed global mean; the deviations from the predicted equilibrium give an indication of the importance of dynamics. Some of the ingredients of the equilibrium calculation, such as clouds, are themselves the consequence of dynamics, however. The mean temperature profiles are now known to a first approximation for all the planets and for the satellites with atmospheres—with the exception of Io. Representative profiles are displayed in Figure 4.4. It is instructive to consider the general characteristics of these atmospheres in light of the wide range in energy input and rotational aspects.

Temperature Profile

Venus provides the most dramatic example of a greenhouse effect. At 740 K, its surface temperature is several hundred degrees warmer than the mean for a bare planet at Venus's distance from the Sun. Thermal radiation is trapped very efficiently, in spite of narrow spectral windows in the near infrared where the radiation can leak out from the surface level. The important greenhouse gases include CO_2, SO_2, and H_2O. While theoretical models can rationalize the high temperatures, in situ measurements of the spectra of the upward and downward intensities have not yet been made. There are uncertainties in opacities at high temperature and pressure, as well as in the abundances of the variable trace constituents H_2O and SO_2. Further laboratory work is needed to establish the frequency dependence of the opacities at these temperatures and pressures.

Mars and Venus exhibit relatively simple thermal structures, with temperature decreasing with height within a tropospheric regime and becoming approximately isothermal at higher levels in a stratosphere (or middle atmosphere). At still greater altitudes a high-temperature thermosphere develops, except on Venus's night side, where infrared cooling by CO_2 is effective and mixing by gravity waves may also transport heat downward. Earth has a similar structure, but with the addition of a warm layer in the middle atmosphere due to absorption of sunlight by ozone.

On the outer planets the tropospheres merge with the planetary interiors, and the temperature profiles are close to adiabatic at deep levels. Above this there is a stable upper troposphere, where the visible clouds are generally located. At still higher levels there is a temperature increase due to absorption of sunlight by CH_4, and then a thermosphere warmed by unknown sources. It is a puzzling problem that for all these planets, the stratospheres and upper atmospheres are warmer than expected from known heating mechanisms. The energy balance is not yet fully understood.

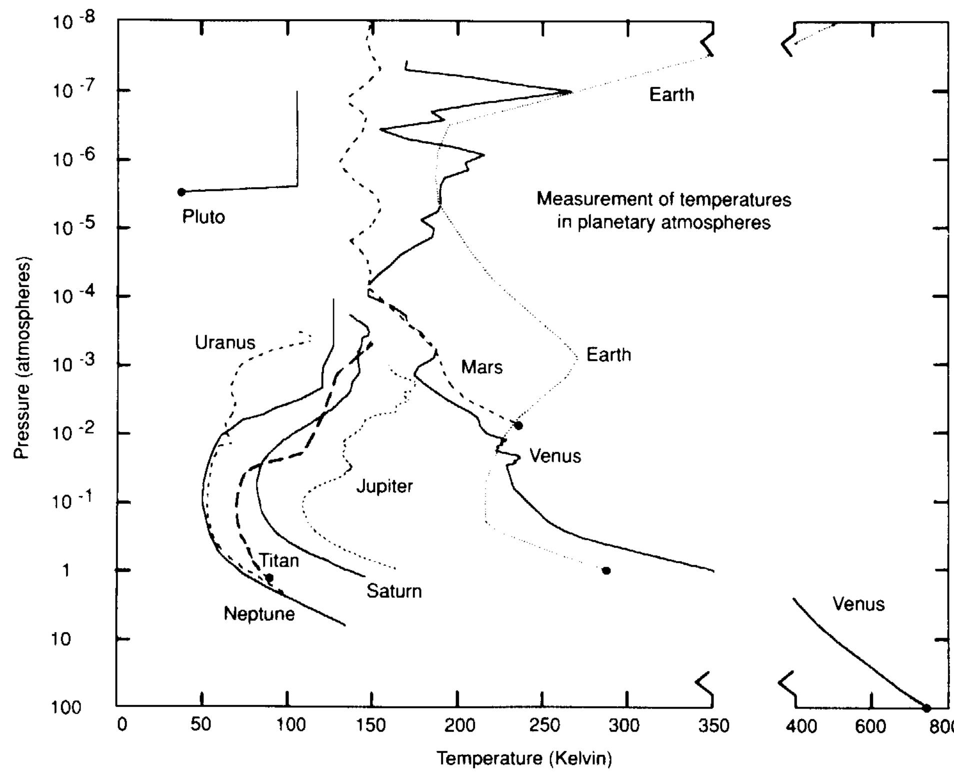

FIGURE 4.4 Temperature profiles of major planetary atmospheres. The profiles of Venus and Mars were measured by in situ descent probes. The profiles of the outer planets, and that of Titan, were inferred from spacecraft and ground-based occultation data. All these profiles refer to a specific time and a single point on the planet, and the small-scale structures are due to dynamical activity. The profile for Earth is the U.S. standard atmosphere. In the cases of the giant planets, the bases of the profiles are the deepest points sampled, so that the basal pressure has no special significance. For the other planets and Titan, it is the surface pressure. Surface values, for those objects with solid surfaces, are indicated by a solid circle. Note the change in the temperature scale between 350 and 400 K.

Atmospheric Mean Flows

Knowledge of the winds in various planetary and satellite atmospheres comes from a variety of measurement techniques. On the outer planets and Venus the tracking of cloud features is possible. Indirect inferences of thermal winds from observations of temperature gradients have been made for all the planets. On Mars and Venus eolian surface features indicate wind directions. For the terrestrial planets some direct information has been obtained from the tracking of entry probes, landed meteorological packages, or balloon-borne anemometers. In the case of the upper atmosphere of Venus, ground-based measurements of Doppler shifts of millimeter wavelength rotational lines of CO, detected on the planet's limb, have been used to measure winds. In general, improved techniques are needed for determination of flow velocities, especially remote-sensing methods that can be used to monitor wind fields and their variations over time.

Over the past few decades the mean zonal flows on all the planets have been characterized, but those of satellites with substantial atmospheres have not. The planetary mean flows are remarkably varied (see Table 4.2). The outer planets and Venus show strong mean flows that cannot be easily explained in terms of a straightforward response to radiative forcing. The mean circulation on Titan has not yet been detected. Earth and Mars have flow regimes that can be understood more simply in terms of the forcing. The eddy characteristics and associated heat and momentum transports are not well determined for any of the planets except Earth.

The diversity of dynamical regimes exhibited on the different planets offers opportunities to understand the effects of different and often competing physical processes in planetary atmospheres. For example, the eddy processes that maintain a rapid spin in the venusian atmosphere almost certainly exist on Earth also but are overwhelmed by other eddy processes that act to create an effective drag. Comparative study will help in understanding both systems. Attempts to comprehend winds theoretically and to model their large-scale character have been most successful for rapidly rotating planets like Mars and the giant planets because much of the dynamical theory developed for Earth is applicable. Even so, major problems remain. Prime among these are (in no particular order):

- The episodic occurrence of planetary-scale dust storms and the apparent regularity of wintertime weather systems on Mars,
- The development and maintenance of the zonal jets and long-lived vortices observed on the outer planets, and
- The influence of latent heat and H_2 ortho- and para-state internal energy conversions on the outer planets.

Several of these items have analogs in the study of the atmosphere and climate of Earth. Good examples are the development and persistence of atmospheric "blocking" (by a high-pressure area that locks weather patterns in place) and the occurrence of interannual variations such as El Niño and its associated Southern Oscillation. Furthermore, both Earth and Mars are known to have mid-winter polar "warmings," while long-term observations of Jupiter's equatorial regions suggest seasonal variations that are dynamically similar to Earth's quasi-biennial oscillation.

Dynamical Regimes

Comparisons between the rapidly rotating terrestrial planets, Earth and Mars, are particularly appropriate within the context of dynamical meteorology. Both have shallow atmospheres forced largely by seasonally varying radiative heating of their surfaces. Given this fundamental similarity, their atmospheres are still sufficiently different (with regard, for example, to latent heating) that observation of atmospheric circulation on Mars can significantly test theories and parameterizations of dynamical processes related to short-term climate change on Earth. In order to adequately characterize the surface-atmospheres interaction, ground stations spanning significant longitudinal, latitudinal, and altitudinal ranges are required. Between 15 and 20 stations are the minimum necessary to acquire useful meteorological data that span latitude, longitude, and elevation contrasts.

The jovian planets also provide an instructive suite of dynamical regimes. All have high-speed jets at low latitudes, but the speeds vary greatly from planet to planet (see Table 4.2). Neptune and Jupiter have huge vortices visible in their atmospheres. The relationships between these different flows and the distinctly individual internal structures and heat sources of Jupiter, Saturn, Uranus, and Neptune are not yet understood. These questions may, to some extent, be amenable to understanding by theoretical modeling, and calculations of the circulation of the giant planets' atmospheres are now being carried out. Nevertheless, eventually it will be essential to obtain measurements of flow and temperature contrasts beneath the visible clouds. This step will require a series of probes to adequately sample latitudinal variations.

Understanding of the dynamical processes of the slowly rotating objects Venus and Titan is even less complete. The dramatic and persistent spin of Venus's atmosphere remains unexplained and is a major puzzle in planetary science. Observations of the motions at cloud-top level, near 70 km elevation, do not reveal eddy stresses that can maintain the spin. It is probable that measurements of flow properties within the lowest two scale heights of the atmosphere (between the surface and about 30 km elevation) will be needed. A velocity precision of 0.1 m/s, which is an order of magnitude better than previous measurements, and a horizontal sampling interval smaller than the planetary radius should be the goal. While the Pioneer Venus probes determined the mean characteristics of the flow, they did not define the nature of eddies.

Atmospheric Response to Forcing

It is useful to compare the responses of the three terrestrial planetary atmospheres to forcing by sunlight, which to a first approximation imposes a simple latitudinal gradient of heating. In spite of having a similar fundamental drive and similar lower-boundary conditions (impermeable surfaces), these planets have quite different general circulations. Free-eddy activity is less frequent on Mars than on Earth. Latitudinal temperature gradients are very strong in Mars's winter hemisphere, and baroclinic instability appears to be confined to these regions. Mars has a more extensive Hadley circulation than does Earth, particularly during dust storm activity. One of the fundamental causes of differences is that the martian atmosphere is a more highly dissipative system than Earth's. Mars's atmospheric mass is smaller and its thermal time constant is shorter (a few days compared to about a month on Earth), and therefore its temperature and motion fields are tightly coupled to the radiative forcing.

Venus is at the other extreme: its thermal time constant is several years, and its latitudinal temperature gradient is very small, while the solar forcing varies greatly between equator and pole. Its general circulation is a rapidly spinning flow that is produced indirectly by a series of energy transformations that are not yet known. The coupling of the atmospheric behavior on Venus to fundamental solar forcing is much more complicated than that on Earth or Mars. It is even possible that the mean states of loosely coupled atmospheric systems with low dissipation are not unique, and that more than one statistically steady "equilibrium" can occur. This issue underlies the question of climate stability on Earth and enhances the importance of comparative studies of Mars, Venus, and Earth.

Another fundamental difference between Earth and Mars is the dust storm activity on Mars arising as a result of its dry, loose surface and strong surface winds. Dust storms occur unpredictably on interannual time scales, but with a strong seasonal trend. The largest storms occur near perihelion in some years, and at these times much of the surface can be completely obscured. In the absence of liquid water, dust and soil transported by the martian atmosphere constitute a major geological weathering process. The albedos of the polar caps and the stratigraphy of the polar layering may also depend importantly on atmospheric dust transport.

For the outer planets, the relationships between fundamental forcing mechanisms and atmospheric configurations are even less obvious. Internal heat supply and insolation are global in scale. On Jupiter and Saturn the response to thermal forcing is multiple jets of alternating sign, with upper tropospheric temperature gradients that actually reverse sign several times between equator and pole. These atmospheres share with Venus's atmosphere the property that thermal time constants are very long compared with the rotation period or the dynamical transport times. The general circulation may be loosely coupled to the forcing mechanisms in these cases as well. There is the additional complication that the thermodynamic energy transformations may involve latent heat release in deep clouds (water, for example), and the importance of these transformations is unknown. Thermodynamic disequilibrium between the ortho- and para-states of molecular hydrogen is known to exist on Jupiter and may occur on the other jovian planets. The heat of conversion is great and may be dynamically important. Spatially resolved observations of the fraction in the para-state are needed to specify this heating rate and could also be used to help infer rates of vertical transport, because the ratio of ortho- to para-states reflects the temperature of the level of origin of the fluid.

Another striking aspect of the giant planets' atmospheres is the lack of a systematic relationship between wind speed and the power of the internal heat source. Although Neptune radiates 20 times less power per unit area than Jupiter (and 400 times less than Earth), its winds are three times stronger than Jupiter's. The explanation may again lie in weak dissipation and consequent uncoupling of the dynamical response from the forcing mechanism.

Comparison of the horizontal winds within the visible atmospheres of the four giant planets reveals two types of circulation. Jupiter and Saturn have a strong eastward (prograde) equatorial circulation with alternating east-west winds that decrease in magnitude toward the poles. Long-lived eddies that absorb smaller eddies are latitudinally constrained. In contrast, the equatorial flows on Uranus and Neptune are westward (retrograde) and jets are much wider relative to the planetary radii. Because of the relative lack of dynamic cloud markers in the atmospheres of Saturn and Uranus, Jupiter and Neptune are the preferred sites for mapping differences in the zonal winds.

For the outer planets as well as for Venus and Earth, it is particularly important to establish the transfers of heat and momentum that result from eddy motions in the atmosphere. These are the fluxes that are generated spontaneously by instabilities and that lead to configurations unrelated to the form of the forcing. At the cloud level the nature of eddies can be determined by remote sensing. On Jupiter and Venus, data on velocity from the Voyager and Pioneer Orbiter missions, respectively, have been used to estimate momentum fluxes, but the results are subject to large errors and have not yet answered major questions. In addition, simultaneous determinations of temperature and velocity are necessary in order to establish heat fluxes, and these measurements have not yet been made.

Upper Atmospheres

Upper atmospheres have their own thermal, dynamical, and chemical regimes. Mars and Venus have cold upper atmospheres (usually with temperatures less than 300 K), whereas Earth's thermospheric temperature lies between 700 and 1500 K. The giant planets have thermospheric temperatures in the range of

400 to 1000 K and are warmer than can be accounted for by current models. Comprehensive measurements of composition, energy inputs, and temperatures are needed before the thermal structure can be understood. The degree to which the large-scale circulation at high levels is driven by small-scale waves propagating upward from more dense regions is uncertain for the upper reaches of all planetary atmospheres, including that of Earth.

While limited escape takes place in the upper atmospheres of all planets, Pluto—because it has the highest ratio of thermal energy to gravitational potential energy at the microbar level—is the most likely case in the solar system for hydrodynamic escape. The adiabatic cooling associated with hydrodynamic escape would have an important effect on the thermal structure of Pluto's upper atmosphere. Within the Pluto-Charon binary system, Charon may collect some of Pluto's escaped atmosphere.

Key Questions

Many questions need to be answered to understand the dynamics and thermal structure of planetary atmospheres. These include (in no particular order) the following:

- What momentum transport processes act within the lower atmosphere of Venus (between elevations of 0 and 40 km) to maintain the atmospheric rotation?
- How do the eddy transport processes in the atmospheres of Titan and Venus (both slowly rotating bodies) compare?
- What causes the episodic behavior of the martian dust storms, and how do the nonseasonal variations within the martian atmosphere compare with those in Earth's atmosphere?
- How are the zonal jets and long-lived vortices generated and maintained within the atmospheres of the giant planets?
- What are the relative contributions of external solar forcing and internal energy conversion in the outer planets?
- What is the nature of the deep circulation within the atmospheres of the giant planets? How deep do the zonal jets extend, and what are the rates of vertical mixing? Can spatially resolved observations of the para-state be used to quantify vertical velocities?
- What is the heat source(s) in the thermospheres of the giant planets? To what extent do vertical wave propagation and saturation contribute as a source of heat?
- Does Pluto have a hydrodynamically escaping atmosphere? Does Charon have a detectable atmosphere?

Climate Change

Climate is determined by the statistical attributes of several atmospheric variables such as temperature, wind, and precipitation; in turn these variables are influenced by the energy transported in solar and planetary radiation, the energy stored and convected by the atmosphere, and the heat brought up from the planetary interior. The immediate and long-term responses of these variables to changes in forcing mechanisms or to spontaneous internal readjustments—climate change—are of fundamental scientific interest for all the planets. In addition, any severe climate change on Earth could jeopardize the long-term survival of our civilization.

It is recognized that changes in climate are caused by compositional changes (through geological and biological processes and, in the case of Earth, through human activities); periodic variations in the orbital elements of a planet; possible modulations in solar luminosity; and the occurrence of catastrophic events such as asteroidal impacts and volcanic eruptions.

Atmospheric composition is a basic climate-forcing mechanism—one that causes the greatest concern for Earth's climate. The massive atmospheres of Venus, Earth, and Titan all allow sunlight to reach their surfaces, yet they trap a significant fraction of the outgoing thermal radiation (most of that radiation in the case of Venus). The resulting increase in surface temperature is known as the greenhouse effect, the magnitude of which depends critically on atmospheric constituents (gases, clouds, aerosols, and dust) that interact with the radiation. Atmospheric gaseous composition may evolve substantially over geologic time (see the section "Origin and Evolution of Planetary Atmospheres," below)—and certainly has done so for Earth—with associated changes in clouds and aerosols. The dust suspended in a planetary atmosphere is also subject to variations as the circulation changes due to forcing by other factors; Mars is a case where the dust loading of the atmosphere is highly variable even from season to season and year to year. Asteroidal impacts and volcanic eruptions will also cause substantial compositional changes to an atmosphere, including dust loading.

Long-Term Changes

In the case of Mars, images show valley networks, resembling terrestrial drainage patterns, distributed widely across the ancient highlands and imply that hydrologic processes were significantly different when the valleys formed than during most of martian history to the present. An early warm climate would provide one explanation of the observations, but the valley formation process, which could have been the result of sapping, may not have required precipitation and runoff. Indeed, understanding the mechanisms for maintaining temperatures above water's triple point in the presence of reduced early solar luminosity is a challenging issue for climate modeling. Sufficient outgassed CO_2 was likely available to form a thick atmosphere early in martian history, but the resultant greenhouse warming does not appear to have been sufficient to sustain liquid water.

Radiatively active atmospheric constituents—water vapor and CO_2—have evidently declined in abundance during martian history. A complete inventory of martian volatiles is required to allow us to understand how the atmosphere and climate have changed with time—a process that is primarily one of geologic exploration. Most of the CO_2 originally in the martian atmosphere is, today, probably incorporated into the surface as carbonate sediments. Water vapor is only a trace constituent of the present martian atmosphere (given the low surface temperatures that cause trapping of most of the available water in the permanent ice caps and in the regolith), but subsurface water may be abundant, as might be inferred from measurements of the D/H ratio in the martian atmosphere. The elemental isotopic compositions of these volatiles need to be determined (an important start having been made by the Viking missions and by current telescopic observations of atmospheric D/H ratios), and their geologic context needs to be established. Near-infrared mapping of the surface by an orbiter could identify carbonate deposits. The thickness of the permanent polar caps should also be better determined by mapping of surface elevations. Long-wavelength radar sounding by the Russian Mars 96 orbiter may provide information about the polar-cap thicknesses and about the presence of subsurface water. A true inventory of the martian volatiles will certainly require the capabilities of mobile landers equipped with sampling and coring devices. Absolute age dating of surface materials will also be required for a full understanding of climate change—a need that currently calls for the return of samples to Earth.

Cyclic Variations

Changes in Earth's climate, recorded by the advance and retreat of global ice sheets over the past million years, mirror cyclic variations in several orbital parameters such as eccentricity and spin-axis orientation (the Milankovich effect). Analysis has shown that such cycles have much larger amplitudes for Mars and could cause large swings in the martian climate with a periodicity of 10^5 to 10^6 years. The sensitivity of the terrestrial and martian climates to these forcing mechanisms remains unknown. On Mars, the permanent ice caps, the laminated deposits that have been mapped in both polar regions, and other sedimentary formations may well contain a record of cyclic climate change. In particular, the formation of the laminated terrain is generally attributed to periodic modulation of seasonal dust storms and of ice deposition resulting from Milankovich-type orbital variations.

The polar laminae show few craters and evidently postdate the valley networks and fluvial features from Mars's early history. This evidence from the Mariner 9 and Viking missions of both long-term and more recent periodic climate change has been among the most exciting discoveries of planetary exploration because of the potential exobiologic significance and because of what may be learned about the terrestrial climate change problem. In most respects Mars is a much less complex planet than Earth, with a simpler hydrology and with little or no biology; therefore, the problems of its climate history should be more tractable.

The martian atmosphere is predominantly CO_2, buffered by a possibly permanent deposit at the south pole; the atmospheric pressure (though probably not the constituents) may well change substantially with the periodic orbital cycle. The atmospheric dust burden changes much more rapidly—seasonally and interannually. Remote sensing from an orbiter is necessary to study the life cycle of dust storms, the distribution and movement of surface dust, and the normal and disturbed circulation of the martian atmosphere. These are important measurements for understanding the feedback of dust on global circulation and for understanding the nature of climate change. The occurrence or lack of occurrence of a global dust storm each year may be indicative of a climate system that is flipping from one attractor to another. Because of the variability of martian weather from year to year, the continuation of orbital observations beyond 1 martian year (about 2 Earth years) would be extremely useful. Some observations of martian atmospheric behavior can also be made from Earth orbit. These cannot match the detailed three-dimensional characterization of the orbiter instruments, but the location and the motion of dust storms, for example, can be monitored. Because of the extremely variable separation of Mars and Earth, these generally require a telescope comparable in resolution to the Hubble Space Telescope. With the increasing sophistication of adaptive optics systems, ground-based telescopes may soon provide the required resolution on a routine basis.

General Circulation and Seasonal Cycles

A better understanding of the present climate of Mars inevitably depends also on understanding its present general circulation—the means by which heat, carbon dioxide, water vapor, and dust are transported. General circulation model simulations have shown that the dramatic martian seasonal surface-pressure variation, measured by the Viking landers, has two comparable components—one due to seasonal exchange with the polar caps and the other due to redistribution of atmospheric mass by the large-scale circulation. The modeling shows that a quantitative understanding of the seasonal CO_2 cycle and of the intimately linked cycles of dust and water requires knowledge of the large-scale seasonally varying pattern of atmospheric pressure and the closely related surface wind pattern responsible for raising and redistributing dust. Orbiters can determine the atmospheric temperature field and the dust and water loading but cannot measure the surface pressure with sufficient accuracy, and the pressure is a crucial dynamic boundary condition. Conversely, information on the surface pressure without data on the thermal field through the interior of the atmosphere is incomplete information. Ideally, the orbiter and lander measurements should be conducted simultaneously, because together they permit the construction of the full three-dimensional circulation. It has long been recognized that an orbiter, together with at least 15 or 20 surface stations, is required to achieve a good characterization of the system.

Cataclysms

The possible role of cataclysmic events in martian climate history is not well understood, although the potential is clear—massive impacts and massive volcanism are obvious processes that have shaped the planetary surface and must have also shaped its climate. Progress in this area calls primarily for the inventory of volatiles discussed above.

Outer Planets

While planetary climate-change studies focus on Mars, Venus (a dramatic example of a "runaway greenhouse"), and Titan, the giant planets are also of potential interest—especially Uranus, where every 84 years the Sun appears to be overhead at one pole or the other because of the planet's extreme obliquity. Voyager measurements (made when the Sun was above the southern pole), however, show that the temperatures at Uranus's two poles are essentially equal, indicating that climate change for the giant planets must occur with very long time constants, given the large thermal inertias of their massive atmospheres. Variations in obliquity also drive climate change on Neptune's satellite Triton and in the Pluto-Charon system.

Key Questions

Of the many questions related to climate change, some key ones are (in no particular order) the following:

- What is the total inventory of volatiles—both elemental and isotopic—on Mars?
- What factors control the annual CO_2, water, and dust cycle on Mars, and the interannual variability of dust storms?
- What is the microphysical structure of the permanent martian polar caps—the mixture of dust and ice as a function of depth?
- What are the composition, structure, and radiative balance of Venus's and Titan's atmospheres as a function of altitude?
- Are the climates of loosely coupled, low-dissipation atmospheres stable?

Origin and Evolution of Planetary Atmospheres

Our understanding of the origin and evolution of atmospheres in the solar system is limited, because current observational evidence cannot separate outcomes that are consequences of initial compositional differences (due to distance from the Sun, local densities, and so on) from outcomes related to ongoing chemical fractionation that has occurred as the planetary atmospheres evolved. It is currently believed that the atmospheres of the inner planets have arisen from several sources: accretion of planetesimals, subsequent outgassing, possible later accumulation of volatiles, and ongoing chemical evolution. However, early conditions led to the loss of much of the original atmospheric material. The current atmosphere is thus a product of subsequent outgassing and secondary acquisition of volatile material by impacts of bodies formed at greater heliocentric distances.

Parallel questions exist for atmospheres in the outer solar system, for which accretion sequences have been proposed. The larger masses of Jupiter and Saturn relative to those of Uranus and Neptune have been described by an accretionary model according to which, depending on the local environment, a protoplanetary core would grow by the condensation of water ice to a critical size of up to 10 to 20 Earth masses. If the local density of the solar nebula were high enough, bodies of this size would create instabilities in the surrounding gases, resulting in the collapse of a hydrogen- and helium-rich atmosphere onto the accreted core.[15]

Determination of Elemental and Isotopic Ratios

Among the fundamental data needed to delineate the proposed atmospheric scenarios are accurate determinations of the elemental abundances in the current atmospheres. Because photochemical and gravitational diffusive separation processes in upper atmospheres lead to the preferential escape of the lighter isotopes of elements, the chemical composition of an atmosphere evolves with time. Isotopic ratios of selected atmospheric constituents preserve information about earlier atmospheric conditions, but this information is frequently masked by the fact that a given element can exist as a molecule and also as an atom and may even be present in more than one phase, for example, gas and ice.

Most of these complications do not arise for the rare gases because they are chemically inert, exist only in the gaseous phase, and vary greatly in molecular weight. Measurements of He/Ar, Ne/Ar, Kr/Ar, and Xe/Ar abundance ratios are useful indicators of the total mass of gas that has cycled through an atmosphere. Similar arguments may be applied to an element whose isotopes show significantly different rates of planetary escape and imply that isotopic ratios, for example, the $^{15}N/^{14}N$ ratio, are a meaningful indicator of the total mass of an individual element that has been cycled through the atmosphere. A more complete knowledge of isotopic ratios, such as accurate values for the ratio of ^{20}Ne to

^{22}Ne, can be used to differentiate between origins as meteoritic material or relatively unfractionated samples of the solar nebula.

Atmospheres of Terrestrial Planets

Many basic problems need to be resolved concerning the fate of constituents of the atmospheres of the inner planets. The simple models of the formation of the solar system would lead one to expect compositional similarities for the atmospheres of the inner planets. Thus large differences in the relative amounts of water in the atmospheres of Venus, Earth, and Mars must be addressed. To resolve the issue of whether or not Mars had an early warm climate, the processes that created the observed channels and valley networks need to be elucidated, and the climatic implications of the processes need to be determined. More specific knowledge of the water budget in the crust of Mars and more accurate determinations of isotopic abundances, for example, the D/H abundance ratios, in the atmospheres of Venus and Mars will help to resolve this issue.

Atmospheres of Outer Planets

Questions relating to the origin of the deep atmospheres of the outer planets are difficult to address because different molecules and particulates form at various depths. To obtain accurate values of C/H, N/H, and O/H ratios, a range of altitudes must be sampled.

Questions exist about the composition of Titan's nitrogen-rich atmosphere. Titan formed concurrently with Saturn but did not accumulate large amounts of hydrogen and helium. A more complete understanding of the chemical and isotopic differences between the atmospheres of Saturn and Titan may provide strong constraints on the ice content of the accreting cores of gas giants. Simple probes carrying mass spectrometers can penetrate deeply enough into the atmosphere of Saturn to obtain significant results and can obtain the equivalent information for Titan down to the liquid-solid surface.

Triton and Pluto most likely formed in the solar nebula, rather than in a local protoplanetary nebula. Each has subsequently experienced violent events. Triton was captured by Neptune, whereas Pluto and Charon underwent some type of mutual capture and/or disruption. Comparative study of the atmospheres of Pluto and Triton may reveal differences in the circumstances of their formation and/or subsequent evolution, in addition to clues about the composition of the solar nebula where these bodies grew. For example, cosmochemical arguments suggest that CO should be the dominant form of carbon in the outer solar system and that objects like Pluto, Triton, possibly Titan, and comets should be preferentially composed of CO rather than CH_4. Yet on Titan the CO/CH_4 mixing ratio is only $\sim 10^{-2}$, whereas CO has not yet been detected in the atmospheres of Triton and Pluto (although we know that some CO must exist in their atmospheres, since the spectral signature of CO surface ice has been detected for both bodies). On Triton and Pluto the CO and CH_4 mixing ratios are important unknowns.

Key Questions

Some key questions pertaining to the origin and evolution of planetary atmospheres are (in no particular order) the following:

- What are the origins of the atmospheres of Venus, Earth, and Mars?
- Why do the atmospheres of Venus, Earth, and Mars have such different amounts of H_2O?
- What are the mixing ratios of both CO and CH_4 in the atmospheres of Pluto and Triton, and what do they suggest about the cosmochemical origins of those atmospheres?
- How have the composition and structure of Triton's and Pluto's atmospheres evolved since the formation of these bodies?

OBJECTIVES

The major objectives for each of the scientific themes relating to planetary atmospheres are given below (in no particular order).

Composition and Chemistry

- Measure the isotopic ratios of the reactive elements H, C, N, and O and of the noble gases to a minimum accuracy of 10% for all substantial planetary atmospheres to enable meaningful comparisons with elemental compositions observed in the Sun, in meteorites, and in other planets. In the case of $^{13}C/^{12}C$, $^{18}O/^{16}O$, $^{15}N/^{14}N$, and D/H—ratios for isotopes in the major molecular species—the requirement increases to an accuracy of 1%.
- For the atmospheres of the giant planets, measure the profiles of the vertical mixing ratios of trace chemical species (e.g., CO and N_2) that can be used to infer both vertical mixing and convection rates and the relative importance of photochemistry to thermochemistry in the troposphere. Also measure the C/H, N/H, and O/H ratios in the giant planets as a function of altitude to understand the cosmochemical origins of their atmospheres.
- Measure the degree of CH_4 oversaturation in the neptunian stratosphere relative to the vapor pressure equilibrium at its tropopause temperature.
- Determine the composition of hazes in the atmospheres of Jupiter and the other giant planets, and also in the atmospheres of Titan, Triton, and possibly Pluto.
- Measure the dominant chemical species that define the basic composition of the atmospheres of Pluto, Charon, Chiron, and Io. Measure both the CO and

the CH_4 mixing ratios in the atmospheres of Pluto and Triton to an accuracy of 100 ppm. If these measurements cannot be accomplished using Earth-based telescopes, then in situ measurements may be required.

- Search for any species in Io's atmosphere with a surface partial pressure of 0.1 nanobar or more.
- Determine the chemical processes that maintain the stability of the CO_2 atmospheres of Mars and Venus and explain the high oxidation state of Venus in its photochemical region in the absence of detectable O_2, by measuring H_2O, O_3, and dust on Mars to differentiate the relative importance of the HO_x and dust cycles and by measuring H_2, O_2, sulfur, and halogen compounds on Venus. Determine the relative importance of heterogeneous versus homogeneous chemistry in the atmospheres of Mars and Venus by measuring haze composition, particle density distributions, and the composition of key chemical species (e.g., H_2O, H_2, and O_3 on Mars and H_2, O_2, sulfur, and halogen compounds on Venus).

Dynamics and Thermal Structure

- Investigate the greenhouse effect in Venus's atmosphere. Measure upward and downward radiation fields as a function of height and frequency. Determine the concentrations of radiatively important trace gases. Laboratory work should be supported to provide detailed frequency-dependent absorption coefficients up to the 100-bar, 750 K limit.
- Study the episodic nature of martian dust storms. Monitor the global circulation of Mars for at least a full martian year at a horizontal resolution greater than 10% of the planetary radius and with vertical resolution of a pressure-scale height or better. Develop better comparative modeling of the atmospheres of Mars and Earth. Simulate the martian climate with global models that have adequate spatial resolution and provisions for dust loading.
- Study the maintenance of the zonal winds and jets within the atmospheres of the outer planets by utilizing probes to determine winds and composition beneath the clouds. Develop models that incorporate latent heat release and hydrogen ortho-/para-state conversion to address questions of heat transfer from the interiors and sources for the momentum of atmospheric jets.
- Monitor the long-term temporal behavior of cloud systems and jets on the outer planets. Episodic activity might be important and can be obtained with Hubble Space Telescope and ground-based instruments with improved sensitivity and spatial definition.
- Determine the seasonal variation of martian surface winds. At least 15 to 20 stations are required to simultaneously sample equatorial, mid, and polar latitudes over a range of longitudes, with some coverage of altitude.
- Define the nature of the momentum transport in the lowest 40 km of Venus's atmosphere to understand the atmospheric rotation. Measurements with

an accuracy exceeding 0.1 m/s are desired. Develop general circulation models to simulate the flow and to assist in interpretation of data.

- Understand heating mechanisms in upper atmospheres. Improve models that incorporate ultraviolet absorption, magnetospheric effects, and propagation of waves. Improve techniques, such as stellar occultations, for determining temperatures and motions in upper atmospheres.
- Determine emissivity and albedo variations over the surface of Pluto and Triton. Search for the presence of an atmosphere around Charon.

Climate Change

- Determine the present climate of the martian atmosphere through a combination of modeling, remote sensing, and in situ measurement. Carry out the atmospheric sounding and synoptic imaging observations over an extended time base. Obtain synoptic data on the interannual variability of global dust storm by telescopic observations. Establish a network of meteorology sensors on the martian surface with sufficient latitude, longitude, and altitude coverage to determine the annual CO_2 cycle caused by exchange between the polar caps, and large-scale circulation. Complement the network observations by temperature and pressure profiling from orbit with global and time-of-day coverage.
- Determine the total inventory of volatiles on and beneath the martian surface, including information about the mineral form and age of these volatiles through analysis of remote-sensing data and the acquisition of new in situ data. Completely analyze the relevant geochemical and geophysical data obtained for Mars by making use of existing information from past missions (specifically the Viking orbital imaging and infrared data) and by acquiring additional global spectral and thermophysical maps. Date and measure the chemical, mineralogical, and isotopic composition of rocks, sediments, and ices collected both at the surface and from the subsurface of representative martian terrains.
- Basic physical chemistry issues with implications for the evolution of the martian atmosphere (and thus its climate) arise in connection with the stability of CO_2 and the escape processes in the upper atmosphere—issues calling for further theoretical analysis, laboratory experimentation, and data acquisition. Acquire orbital measurements of the fluxes of neutral and ionized molecules in the martian thermosphere as a function of latitude, time of day, season, and solar activity.
- Cyclic climate change also represents a broad challenge calling for a detailed vertical characterization of dust and ice mixtures in young sedimentary deposits. Measure the microphysical and chemical structure of the laminated terrains and/or permanent caps of the polar regions to a depth of at least 1 m. This depth should correspond to a time record spanning several hundred-thousand years, covering the full Milankovich cycle.

Origin and Evolution of Planetary Atmospheres

- To achieve good progress, obtain isotopic and rare-gas ratios for Venus, Mars, Jupiter, and either Uranus or Neptune. The relevant quantities include He/Ar, Ne/Ar, Kr/Ar, Xe/Ar, $^{15}N/^{14}N$, and $^{20}Ne/^{22}Ne$ ratios, since they can be used to differentiate between meteoritic or relatively unfractionated solar-nebula material as sources of origin. COMPLEX reiterates the recommendations made in one of its previous reports that the minimum accuracy should be 10%, and that, in the case of $^{13}C/^{12}C$, $^{18}O/^{16}O$, $^{15}N/^{14}N$, and D/H ratios in the major molecular species, the requirement increases to an accuracy of 1%.[16]
- Obtain better information about the volatiles on Mars, knowledge of which is particularly important. Complete answers will probably require subsurface sampling. However, progress will be made by determining the seasonal variation of atmospheric water and dust fluxes in addition to the surface deposits of volatiles.
- Measure the CO and CH_4 mixing ratios on Pluto and Triton.
- Measure to an accuracy of 30% the C/H, N/H, and O/H ratios in the giant planets as a function of altitude relative to the respective solar ratios.
- Better understand the processes that allow atmospheric loss and escape and, in particular, how various processes affect various species, thereby causing an atmosphere's composition to change with time.

WHAT TO STUDY AND WHERE TO GO

Mars

The martian atmosphere is a high-priority region for study. It presents questions of climate variability, atmospheric origin, chemical stability, and atmospheric dynamics. Many of these questions are of particular interest among a broad community because Mars is similar enough to Earth to allow scientifically useful comparisons. Particular emphasis should be placed on long-term monitoring of dynamical behavior with good spatial resolution, such as can be performed by an orbiter. Surface meteorological stations, preferably accompanied by use of an orbiter, are the next step. Eventually, subsurface volatile reservoirs will need to be investigated to reach an understanding of atmospheric and climate history.

Jupiter

Jupiter is the prototypical outer planet, and the most accessible. At Jupiter, measurements can address the questions of why the outer planets have stable jets, how heat is transported from the interiors, how giant ovals are maintained, how clouds are formed and how their colors arise, how photochemical and thermochemical activity is balanced by vertical transport, and how equatorial jets are generated. Many of these questions are of broad interest because of the similarity of the outer planets to other natural systems, such as oceans or stars. Voyager, Galileo, and Cassini have made or will make extensive measurements from the cloud-top level upward, and the most pressing need is to extend such measurements downward to increase the knowledge gained by such experiments. The next generation of spacecraft should include probes that can measure the spatial variability of chemical and thermodynamic quantities beneath the clouds.

Venus

Venus poses perplexing questions of heat balance and circulation and will be a rewarding target for deep probes that can determine the motions and radiation field near the surface. The chemistry of the atmosphere and cloud system also is not well understood and will require determining vertical profiles of trace gases at several locations on the planet.

Outer Planets

Neptune and Triton offer the opportunity to study, respectively, a dynamically active atmosphere of an outer planet and a seasonally varying frost-controlled atmosphere with possible geyser activity. The abundance of CH_4 in the stratosphere of Neptune may have important implications for the general question of stratosphere-troposphere exchange.

The thin atmospheres of Pluto, Charon, Io, and possibly Chiron present questions about frost-controlled seasonally (or diurnally) varying atmospheres. These bodies are interesting because the surface-atmosphere interaction is strong. The surface albedo pattern may determine the distribution of the frost and the quantity of atmosphere.

Telescopic Studies

A great deal of atmospheric science can be done from Earth, or from Earth orbit, especially with instrumentation that provides improved spatial resolution. Activity in the atmospheres of the outer planets can be monitored for long-term variability. Upper atmospheric temperature profiles can be deduced from stellar occultation data. Monitoring of the night side of Venus in the near infrared can provide chemical and dynamical information from beneath the clouds. Changes in the abundances of thin atmospheres, such as Pluto's, can be deduced from stellar occultation data.

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RINGS

Planetary rings, which for centuries were thought to be unique attributes of Saturn, have recently been observed around all the giant planets.[17] Surprisingly, each ring system is distinctive. The rings of Jupiter are extremely tenuous and contain significant amounts of short-lived dust, suggesting that they are continually regenerated. Saturn's rings, which are predominantly composed of water ice particles that are centimeters to meters in size, are broad, bright, and opaque; they exhibit the most diversity in their organization and variety. Uranus's narrow, slightly noncircular and nonequatorial bands, composed predominantly of dark boulders, reside within an extensive structured disk of dust that is invisible from Earth. Neptune's rings are distinguished by one ring that contains four prominent arcs restricted to a small range of the circumference. (Table 4.3 summarizes knowledge of the various ring systems.)

All rings lie close to their planet's equatorial plane, and most are within their planet's Roche limit, where tidal forces would tear asunder a self-gravitating fluid body; they also extend out into the planet's magnetosphere and, in the case of Uranus, dip down within the upper reaches of the planetary atmosphere.

DESCRIPTION OF RINGS AND RELEVANT PROCESSES

Saturn's ring system was first spotted by Galileo Galilei in 1610, but the nature of the rings was not correctly identified until the observations and insight of Christiaan Huygens in the late 1650s. The ring systems of the other giant planets were not discovered until the past 15 years. Uranus's system was first identified in 1977 during a stellar occultation that was best observed from NASA's Kuiper Airborne Observatory. Jupiter's rings were unambiguously seen by Voyager 1 in 1979 but had been inferred earlier from charged particle absorption signatures obtained by Pioneer 10. Neptune's arcs eventually made their presence known in a 1984 stellar occultation observed simultaneously at three ground-based telescopes.

The structure of the rings and their composition differ among the various planets and, to a lesser extent, within each ring system. The most elaborate set of rings, which also contains the widest range of identified processes, is Saturn's system. The general forms of the ring systems surrounding the four giant planets are illustrated in Figure 4.5.

Among the rings, the following structural features are found: vertical thicknesses that are generally small compared to horizontal extent but are substantially greater than the average particle size; significant and abrupt variations in opacity, including dark lanes, gaps, and sharp edges; eccentric and inclined rings; spiral density and vertical bending waves as well as gravitational wakes; variations in azimuthal brightness; arcs and clumps; and other time-variable phenomena including incomplete, kinked, and apparently braided rings. Some of these features have been interpreted as having been caused by gravitational interactions with nearby moons (as well as distant ones), especially at the locations of orbital resonances. Nevertheless, most ring features remain unexplained.

Beyond the gravitational perturbations due to embedded and adjacent small moons (many of which were contemporaneously discovered by the Voyager spacecraft), ring particles interact with the magnetosphere via charging, plasma drag, and dynamical forces with the ambient electromagnetic field. Electrostatic effects may lift small particles off the surfaces of the larger ring particles to create "spokes," the dark, roughly chevron-shaped lanes discovered by Voyager in the midst of Saturn's B-ring. Small particles at the inner edge of rings may experience gas drag from the extended planetary atmosphere.

The size distribution of ring particles extends from submicron dust, through meter-sized particles, to small embedded moons, including the recently discovered Pan, about 10 km in radius. Theoretical expectations, but only limited data, support the idea that ring particles segregate in size, both radially and vertically.

The composition of ring particles is well known only for Saturn. Spectroscopic, thermal, radio, and neutron measurements combine with estimates of mass density to suggest that Saturn's ring particles throughout are almost entirely water ice with just a little contaminant to account for an observed reddening. For the other ring systems, the particles superficially resemble the contiguous small moons; probably these rings contain silicate and, in the cases of Uranus and Neptune, possibly carbonaceous material. In Saturn's rings, color and albedo variations hint at modest compositional differences across various radial regions of the rings.

For Saturn's and Uranus's rings, occultations of spacecraft radio signals at two wavelengths have provided information on particle sizes in the range of roughly 1 cm to 10 m at a number of locations (unfortunately excluding Saturn's B-ring because its high opacity prevented transmission of the signal). The derived differential size distributions of particles whose radii span several orders of magnitude satisfy power laws with indices ranging between 2.5 and 3.5. Smaller particles are inferred from photometry and from the different ring opacities measured in stellar occultations at a spread of wavelengths. The relative fraction of dust differs significantly across the rings; some of the dusty rings have very steep size distributions.

We have a first-order understanding of the dynamical processes in rings, much of it based on previous work in galactic and stellar dynamics. The rings are a kinetic system, in which the deviations from perfect circular, equatorial motion can be considered as random "thermal" velocities in a viscous fluid. Unfortunately, the models are often idealized (e.g., all particles are treated as hard spheres of the same size) and cannot yet predict many phenomena in the detail given by spacecraft observations and Earth-based occultations (e.g., sharp edges or specific wave profiles).

All of the ring systems show many youthful features: Saturn's ice is bright

TABLE 4.3 Ring Particle Properties

Planet	Ring	$R(R_p)^c$	Large Particles[a]			Albedo[g]	Small Particles[b]			σ (g/cm^2)[h]	M (g)[j]
			τ_{large}[d]	r (cm)[e]	P_{large}[f]		τ_{dust}[d]	r (μm)[e]	P_{dust}[f]		
Jupiter	Halo	(1.40)-1.72	$<1\times10^{-6}$				2×10^{-6}	[0.3-16]	>2.5		
	Main	1.72-1.81	3×10^{-6}	>1	[3]	[0.015]	2×10^{-6}	<0.3->16	2.5±0.5	$>5\times10^{-6}$	$>3\times10^{14}$
	Gossamer	1.81-(3)	$<1\times10^{-7}$				1×10^{-7}	[0.3-16]	[2.5]		
Saturn	D	1.11-1.24	(0.01)								
	C	1.24-1.52	0.05-0.35	1-(100-500)	3.1	0.12-0.30				0.4-5	1×10^{20}
	B	1.52-1.95	0.8-2.5	1-500	2.7-3.0	0.5-0.6	<0.01	0.1-1000		60-100	1.4×10^{22}
	Cassini Division	1.95-2.02	0.05-0.15	1-750	2.8	0.2-0.4				5-20	4×10^{20}
	A	2.02-2.27	0.4-0.9	1-400	2.7-3.0	0.4-0.6	<0.01-0.03	0.1-1000		20-50	4×10^{21}
	F	2.32	0.02	≈1	3.3±0.2	0.6	0.1	[0.1-10]	4.1±1.1		
	G	2.75-2.88	10^{-8}	>25			1×10^{-6}	0.03-0.5	6±1		
	E	(3)-(8)	$<2\times10^{-7}$				1.5×10^{-5}	1.0±0.3			
Uranus	U2R	(1.49)	<0.001								
	6, 5, 4, α, β, η, γ, δ	1.60-1.84	0.2-0.6	>1		0.010-0.018	$(2\text{-}8)\times10^{-4}$	[1]	[2.5]	2-10	3×10^{17}
	Outer dust band	1.84-1.91					2×10^{-5}	[1]	[2.5]		
	λ	1.91	<0.05				0.1-0.2	0.1?			
	ε	1.95	0.5-2.3	>70	[3]	0.018	2×10^{-3}	[1]	[2.5]	25	5×10^{18}

Neptune	Galle	1.69	(3-12)×10^{-5}	[0.015]	5×10^{-3}	[2.5]
	Leverrier	2.15	0.005	[0.015]	0.01	[2.5]
	Lassell	2.15-2.4	(3-12)×10^{-5}	[0.015]	5×10^{-3}	[2.5]
	Adams	2.53	0.01	[0.015]	0.005	[2.5]
	Adams arcs	2.53	0.03	[0.015]	0.04	[2.5]

[a]Large particles are those larger than approximately 1 mm.
[b]Small particles are those less than 1 mm.
[c]The radius of the ring relative to that of the planet.
[d]The optical depth—roughly the fraction of the surface area covered by ring particles.
[e]The range of particle sizes.
[f]The index of the power law describes the differential size distribution of the particles.
[g]Albedo—a measure of the reflectivity of the surface.
[h]The surface density of the ring.
[j]The total mass of the ring.

NOTE: Quantities in brackets are assumed, not measured. Quantities in parentheses are uncertain. A range of values (except for particle sizes) indicates actual variation through broad regions of the ring, excluding narrow gaps or ringlets. For a more detailed description of this table, see Nicholson, P.D., and L. Dones, "Planetary Rings," *Reviews of Geophysics (Suppl.)* 29:313-327, 1991.

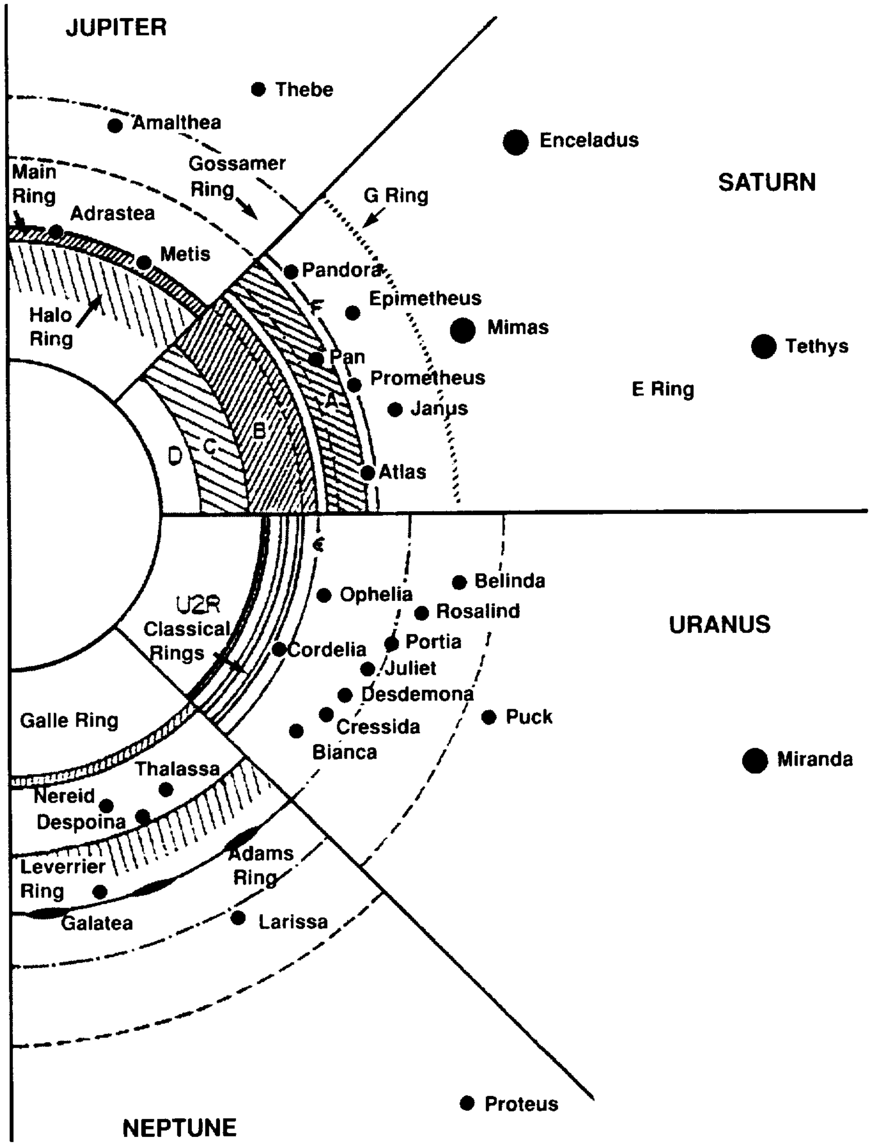

FIGURE 4.5 A comparison of the four known planetary ring systems (shown by solid circles), plus their associated satellites, scaled to a common planetary equatorial radius. The density of cross-hatching suggests the relative optical depths of different ring components (see Table 4.3 for actual values). Synchronous orbit is indicated by a dashed line; the fluid tidal breakup (Roche) limit for a density of 1000 kg m^{-3} is indicated by a dot-dashed line.

and yet is continually bombarded by dark carbonaceous material from comets; Uranus's rings are narrow and yet should be dragged inward by the planet's atmosphere; Neptune's arcs are constrained to a small range of longitude but should shear apart; and Jupiter's particles are so small that they will be eliminated in much less than a millennium. The angular momentum transferred in asymmetric gravitational interactions between rings and nearby moons should have caused them to spread much further apart over the eons than they are observed to be. Further, the small moons discovered adjacent to the planets by Voyager could not have survived the flux of interplanetary meteoroids for the age of the solar system; in much less time, according to present models, these small moons would be shattered by interplanetary impactors. This realization provides a potential solution to the problem presented by young rings: such impacts may not only destroy the moons, but may also regularly recreate the ring systems that are gradually spreading and being ground to dust. Thus, the moons not only sculpt the rings' structure, but may also be the reservoirs for past and future ring systems. Of course these reservoirs themselves are gradually being depleted.

Our description of the various ring systems remains incomplete, especially in our knowledge of the overall size distribution and the composition of the ring particles (which, in fact, may vary within each system). We need to understand the vast differences among the various planetary ring systems. Do they indicate different origins, different environments, or merely different random outcomes of the same stochastic processes of ring creation and destruction? We need accurate measurements of the three-dimensional morphology of the rings to compare with predictions from present models of ring dynamics so as to refine such models.

Questions about the ages of the rings, their recent origins, and their history have been brought into sharp focus by spacecraft observations of many apparently youthful features as well as by calculations indicating that the present rings could not have persisted for the age of the solar system. Perhaps the most important question is whether our understanding of present processes in planetary rings can be fruitfully compared with similar processes in the early solar nebula to explain the origin of the planets and satellites in a flat disk of interacting particles, dust, and gas. We can also hope to apply this understanding to other flattened, rotating systems like galaxies and accretion disks.

Some of the questions arising from our current understanding of rings include the following:

- What features of rings are time-variable and what causes these variations?
- How is angular momentum transferred between ring components, and between the rings and satellites?
- Do all ring systems contain moonlets? If so, how many are there, and where are they located?
- How old are various features of the rings? How are these ages to be interpreted?

• What influences do electromagnetic processes have on the rings and, in turn, how do rings affect magnetospheric characteristics?

OBJECTIVES

To understand planetary rings, three major objectives must be achieved by any exploration program:

• Measure radial, azimuthal, and vertical structure at high spatial resolution and multiple times in order to distinguish between spatial and temporal variations. This involves high-resolution imaging, as well as radio, stellar, and solar occultations from planetary orbit. In addition, ground-based stellar occultations should be fully utilized to provide the absolute radial scale of the rings, an accurate orientation of the planet's rotation axis, and the orbital elements of any narrow rings.

• Determine the complete size distribution and composition of the ring systems at multiple locations. This size distribution should extend from the smallest transient dust particles up to the moonlets located within and abutting the ring system. Radio occultation, spectroscopy, and photometric measurements should contribute to this objective.

• Develop models of ring processes and evolution that are consistent with the best ground- and space-based observations. These models should establish the relation of ring structures to moons, atmospheres, and magnetospheres and, ideally, should allow connections to be made to understand the early solar system. This development will depend on an improved description of rings and may provide a direct benefit to our understanding of the origin of planetary systems. It will require close collaboration between observers and modelers.

WHAT TO STUDY AND WHERE TO GO

Many of the above objectives are likely to be accomplished with Galileo's observations of Jupiter's ring and, especially, with Cassini's extended visit to Saturn. Ground-based observations of stellar occultations can characterize the spatial and temporal variability of the narrow rings of Saturn, Uranus, and Neptune; they may also refine the precession rate of Saturn's rotation pole. In the case of Neptune, a primary goal is to determine the radial structure of the arcs. The limited number of images that Galileo can obtain may require that subsequent missions plan imaging observations to define the ring's structure, particle size distribution, and possible variability. When spacecraft are sent to Uranus and Neptune, ring observations should be taken in the normal course of mission operations.

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MAGNETOSPHERES

The various bodies in the solar system are not separated by great voids of vacuum but are interconnected by a complex system of energetic plasmas (ionized gases) and magnetic fields. A magnetosphere is that region of plasmas and other materials surrounding a planet or other solar-system object that is under the influence of a magnetic field generated within, or induced in the vicinity of, the central object. In *Strategy for Exploration of the Inner Planets: 1977-1987*, COMPLEX regarded "an understanding of the fundamental processes governing the solar wind's interaction with planets as a major goal of solar-system exploration and recommend[ed] that a global characterization be obtained of each planet's interaction with the solar wind."[18] Studies of magnetospheres are significant for:

- Understanding the processes that acted when the solar system was forming;
- Characterizing the way that the solar and planetary systems now function; and
- Illuminating fundamental processes that operate within astrophysical plasmas throughout the universe.

Interactions between magnetized plasmas, dust, and neutral gases are thought to have played an integral role in the formation of the Sun and its planetary system out of the solar nebula; as yet, the manner and level of that role have not been determined. By studying similar interactions today in such natural laboratories as Saturn's dusty magnetosphere or in the vicinity of comets, it may be possible to build more complete models of how the solar nebula may have evolved (cf. Chapter 3). The relevance of dusty, gaseous plasma interactions to the evolution of the solar nebula needs more attention from researchers in the planetary magnetosphere and related communities.

Plasma electrodynamics plays a contemporary role in the disposition, evolution, and transport of materials. For example, dust grains within rings and elsewhere become electrically charged (forming the so-called dusty plasmas[19]) and are transported by means of electromagnetic accelerations, as seen, for instance, in the spokes of Saturn's rings and the high-velocity dust streams emanating from Jupiter. Surfaces can be damaged or chemically modified via energetic particle radiation (e.g., at Uranus and Neptune), apparently resulting in icy moons and rings with extremely dark, carbonaceous surfaces. Charged-particle precipitation into planetary atmospheres can lead to the heating of the upper atmosphere and enhanced ionization, and can affect upper-atmospheric chemistry. At Earth, the precipitation of MeV electrons and solar protons with energies of tens of MeV can significantly alter ozone concentrations in the lower mesosphere. The distribution of neutral gases can be altered by plasma processes. Thermospheric winds are driven by strong coupling of Earth's upper atmosphere to the large-scale plasma motions in Earth's magnetosphere. Also, solar wind interactions may have significantly modified the evolution of rarified atmospheres such as that of Pluto.

Planetary magnetospheres, and the solar wind in which they are embedded, are the only astrophysical plasma environments that are accessible for in situ observation. Thus they are plasma laboratories for observing processes that operate throughout the universe but that cannot be studied directly. Besides their inaccessibility due to large distances, parameter ranges and length scales of astrophysical plasmas are not generally attainable in laboratory plasma experiments. For example, close comparisons have been drawn between the so-called magnetospheric substorms and solar flares. A substorm is a sudden, global restructuring of magnetospheric systems associated with dynamic auroral displays, plasma heating, charged-particle energization, and Joule heating of the ionosphere. By studying magnetospheric substorms much has been learned about the fundamental physics by which magnetic energy (from stressed magnetic fields) is dynamically converted into other forms of energy within astrophysical plasmas. The energization of magnetospheric charged particles also models aspects of cosmic-ray acceleration. Pulsar magnetospheric processes and astrophysical jets have parallels within planetary magnetospheres.

The in situ sensing of the properties of planetary magnetospheres provides ground truth for the inferences that come from the remote sensing of distant astrophysical objects. The messengers of many astrophysical observations, from X-rays to radio waves, rely on plasma emission processes. Most planetary radio emissions are now classified under two quite broad generation mechanisms: the cyclotron maser instability and electrostatic wave mode conversion. In situ observations of the underlying plasmas have allowed for a much more mature and tested theory for the emission mechanisms; accordingly, extrapolation to other astrophysical settings is more straightforward. The archetypical example of how ground truth is established through the use of remote-sensing and in situ observations is the general agreement between the Voyager ultraviolet measurements of the Io torus and the subsequent confirmation of densities, temperatures, and composition by in situ plasma and plasma wave observations. It is noteworthy that the correct interpretation of the observed ultraviolet emission relied on in situ measurements that showed local thermodynamic equilibrium to be violated, in contrast to the usual assumption for astrophysical plasma.

From a practical standpoint, it is a goal of magnetospheric studies to develop "global" understanding. However, because of their vast volumes and a wide range of time scales, magnetospheres are poorly sampled by spacecraft measurements that are typically taken at discrete positions that change slowly compared to many of the fundamental time scales of the system. Since orbital missions provide multiple passes through magnetospheric systems, they clearly provide more information than flyby missions. For this reason, the Galileo and Cassini orbital missions should dramatically improve our understanding of how the jovian and saturnian magnetospheric systems, respectively, operate over global distance scales and long time scales.

Aspects of the overall global behavior of Earth's magnetosphere have been clarified by the use of powerful simulation models of physical processes that allow the extrapolation of localized measurements to greater scales. Such models will likely be applied to extraterrestrial magnetospheres as scientific understanding of these environments matures.

Global views of magnetospheric processes may be most directly obtained by the remote sensing of magnetospheres. Improved auroral imaging (coupled with in situ observations of particle acceleration regions or precipitation processes) can show how the aurora "maps" to distant magnetospheric regions. Moreover, new techniques are becoming available that allow direct imaging of the enormous breadth of planetary magnetospheres. These approaches sense one of the several different types of emissions with which planetary magnetospheres "glow." These emissions include:

- Line emissions at ultraviolet to optical wavelengths from magnetospheric plasmas;
- "Energetic neutral atoms" (ENA) that result from charge exchange between energetic ions and cool, neutral gases; and
- Photons that are produced as solar photons resonantly scatter off magnetospheric ions and neutrals.

The magnetosphere of Jupiter has been monitored via ground-based, Earth-orbiting, and spacecraft instruments for 20 years. An early-generation "ENA camera" will be on board the Cassini spacecraft. The combination of global images together with in situ measurements will provide unprecedented constraints on saturnian magnetospheric processes.

In previous reports, COMPLEX has provided numerous recommendations relating to the importance of magnetospheric science in the exploration of the solar system.[20-23] Those recommendations are not repeated here, but COMPLEX has adopted them as a basis for this section of the present report and suggests additional studies where the field has advanced beyond those recommendations. In addition, the Committee on Solar and Space Physics of the Space Studies Board and the Committee on Solar-Terrestrial Research of the Board on Atmospheric Sciences and Climate are currently devising a joint strategy for space physics that overlaps, to some degree, the material presented in this section.[24] That study and this one were undertaken with a moderate level of interaction, and the conclusions of both do not appear to conflict in any significant way. Nevertheless, the points of view and the emphases are somewhat different for the two reports.

This section on magnetospheres begins with a brief outline of the status of observations of planetary magnetospheres and an extensive discussion of the various types of magnetospheric configurations found in the solar system. As in the three other major sections of this chapter, a comparative approach is used, and topics associated with contemporary studies of planetary magnetospheres are addressed in terms of four broad scientific themes:

1. Plasma and energy budgets,
2. Auroral processes and magnetospheric dynamics,
3. Gas-dust-surface interactions with plasmas, and
4. Fundamental plasma processes.

Given limited space, this section does not address in detail the magnetospheric community's specific activities with regard to all of the particular regions of magnetospheres, including, for example, the magnetopause, the magnetotail, the radiation belts, the magnetosphere-ionosphere interface, and others. These regions will be invoked within the different thematic areas where appropriate for illuminating the broad issues. Each such section highlights the key questions remaining to be answered. Following the discussion of the four scientific themes is a section outlining objectives that need to be addressed to further studies of planetary atmospheres. The final section, "What to Study and Where to Go," identifies the most important studies to be performed and planetary bodies to investigate to enhance our understanding of magnetospheres.

DESCRIPTION OF MAGNETOSPHERES

Status of Observations

With the completion of the grand tour of the outer planets by the Voyager spacecraft, the initial survey of the planets' plasma environments is mostly complete.[25] Localized measurements of subsets of the following are now available: magnetic fields, electric fields, plasma ion and electron densities and temperatures, energetic charged-particle intensities, plasma and radio wave properties, and auroral brightnesses. Even so, current understanding of the plasma environments surrounding most solar system bodies is quite rudimentary. For most planets, the basic magnetospheric configuration and the low-order terms in a spherical harmonic expansion of the intrinsic magnetic field, if one exists, are known. The fundamental sources and sinks of plasma are recognized, and there is some idea of the primary energy sources. Plasma data are available along one to a few cuts through the magnetosphere along trajectories that were determined by the constraints of Newtonian mechanics rather than by their merits for magnetospheric exploration. For most of the bodies, spacecraft data were obtained within the region of interest for periods generally less than, or roughly similar to, the basic time scales of the magnetospheres themselves. For other members of the solar system, such as Mars, Pluto, and comets, even less is known.

The planets Mercury, Earth, Jupiter, Saturn, Uranus, and Neptune all have intrinsic magnetic fields. In contrast, Venus has a negligible magnetic field but does have an "induced magnetosphere" due to the solar wind interaction with Venus's ionosphere. Currently only an upper limit can be placed on the strength of Mars's magnetic field. With no in situ or radio-astronomical observations available at all, Pluto's plasma environment is a mystery. Given the expectation of little or no intrinsic magnetic field and a weak atmosphere, Pluto's plasma environment is expected to be similar to that of either Venus or a comet.

With regard to other bodies, first-order plasma and field measurements have been made of the induced magnetospheres surrounding comets Giacobini-Zinner, Halley, and Grigg-Skjellerup. While considerable information is available on the interactions of the ambient planetary magnetosphere with Io and Titan, much less is known about the plasma interactions involving most of the other moons of the outer planets (e.g., Triton and Phobos). Galileo's encounter with the asteroid Gaspra provided a hint (albeit controversial) that this body has an intrinsic magnetic field that affects its interaction with the solar wind.

The quality and the quantity of the available scientific data differ considerably for the various solar system bodies that have been visited by spacecraft. For example, the 14 years of magnetospheric data that have been returned by Pioneer Venus represent, by far, the most extensive data set available for a planet other than Earth. In contrast, the magnetosphere of Mercury has been transited only twice, with each encounter producing less than an hour's worth of data from a very limited instrumentation package; no wonder this magnetosphere is puzzling! Jupiter has now been surveyed by five flybys, most recently by the Ulysses spacecraft in 1992, and will be visited by the Galileo orbiter. Saturn has had three visits while Uranus and Neptune have had one each. The former Soviet Union's Phobos spacecraft returned data for only a few weeks from its orbit around Mars before failing.

Since the underlying plasma-physical processes are the same from one magnetosphere to the next, most understanding about the magnetospheres of nonterrestrial planets comes from either qualitative or quantitative analogies with Earth's magnetosphere. What is truly surprising, however, is that many of these similarities hold despite striking differences in magnetospheric configurations, plasma, and energy sources, and other fundamental variations in the magnetospheric environments. The converse is also true: our appreciation of terrestrial magnetospheric physics has been enhanced by observing the full range of phenomena and processes under vastly different parameter regimes. In this sense, the solar system has served as an excellent plasma laboratory that cannot be easily duplicated.

Magnetospheric Configurations in the Solar System

For most planets the gross features of the magnetic field's configuration have been determined, and it is known how the ambient plasma environments are influenced by the solar wind. Table 4.4 summarizes some characteristics of known solar system magnetospheres. For nonmagnetized bodies, such as Venus and comets, the magnetic field carried by the solar wind effectively induces a magnetosphere by being draped around the object. Figure 4.6 is a schematic of an induced, cometary magnetosphere. At Venus, this draping is predominantly a consequence of a conductive ionosphere, while for comets the draping is caused by substantial mass-loading engendered by the continuous ionization of outflowing neutral gases. These nonmagnetized objects therefore respond to the solar wind in a way greatly different from the terrestrial magnetosphere. While a shock wave forms upstream of the obstacle within the supersonic solar wind, the solar wind interacts directly with the ionosphere (in the case of Venus) or with the comae (in the case of comets). Mass loading at a comet may occur over such an extended region that the bow shock can become somewhat indistinct (hence the use of the term "thick bow shock" in Figure 4.6).

The interactions between the solar wind and the magnetospheres of the magnetized planets Mercury, Jupiter, Saturn, and Uranus are similar to the terrestrial case in many respects (see Figure 4.7 for a schematic). At a magnetized planet, the solar wind interacts with the planetary magnetic field, rather than the ionosphere or outflowing neutral gases. In Figure 4.7, the "magnetopause" marks the separation between regions of direct influence by the planetary magnetic field and the regions where solar-wind influences predominate. At the present time the dipole moments of the planets listed above are oriented roughly perpendicular to the solar-wind flow; a two-lobed magnetotail with a central plasma sheet extending thousands of planetary radii in the anti-sunward direction is a common feature of these magnetospheres.

At Neptune, the only "pole-on" configuration of a planetary magnetosphere was observed because of the large tilt between this planet's spin axis and its dipole magnetic axis. (At the time of the Voyager encounter the planet's magnetic north pole sometimes pointed directly into the solar wind.) This orientation changed as the planet rotated so that the magnetosphere as a whole (including, most dramatically it is presumed, the magnetotail) underwent very dynamic reconfigurations between its pole-on situation and a terrestrial-like orientation twice during every 16.1-hour planetary rotation. Unfortunately the Voyager trajectory did not allow a full exploration of this unique configuration so that some key theoretical predictions cannot be tested by available data. Uranus, also having a very tilted magnetic configuration, should as well display this diurnal reconfiguration during certain phases of its orbit around the Sun (e.g., most prominently at the year 2000 and every 14 Earth-years thereafter).

The configuration of a magnetosphere with an Earth-like field orientation is shown schematically in Figure 4.7. Here, Jupiter's magnetosphere serves as a model. The most energetic particles (those with energies ranging from a few to tens of MeV) make up the well-known Van Allen or radiation belts. At Jupiter these belts separate into several regions, one at the innermost portion of the hot plasma population identified in the diagram, and other regions planetward of the "Io torus" that are the source of synchrotron radiation known as decimetric radiation. The acceleration processes for some of these most energetic particles are not well understood, even at Earth.

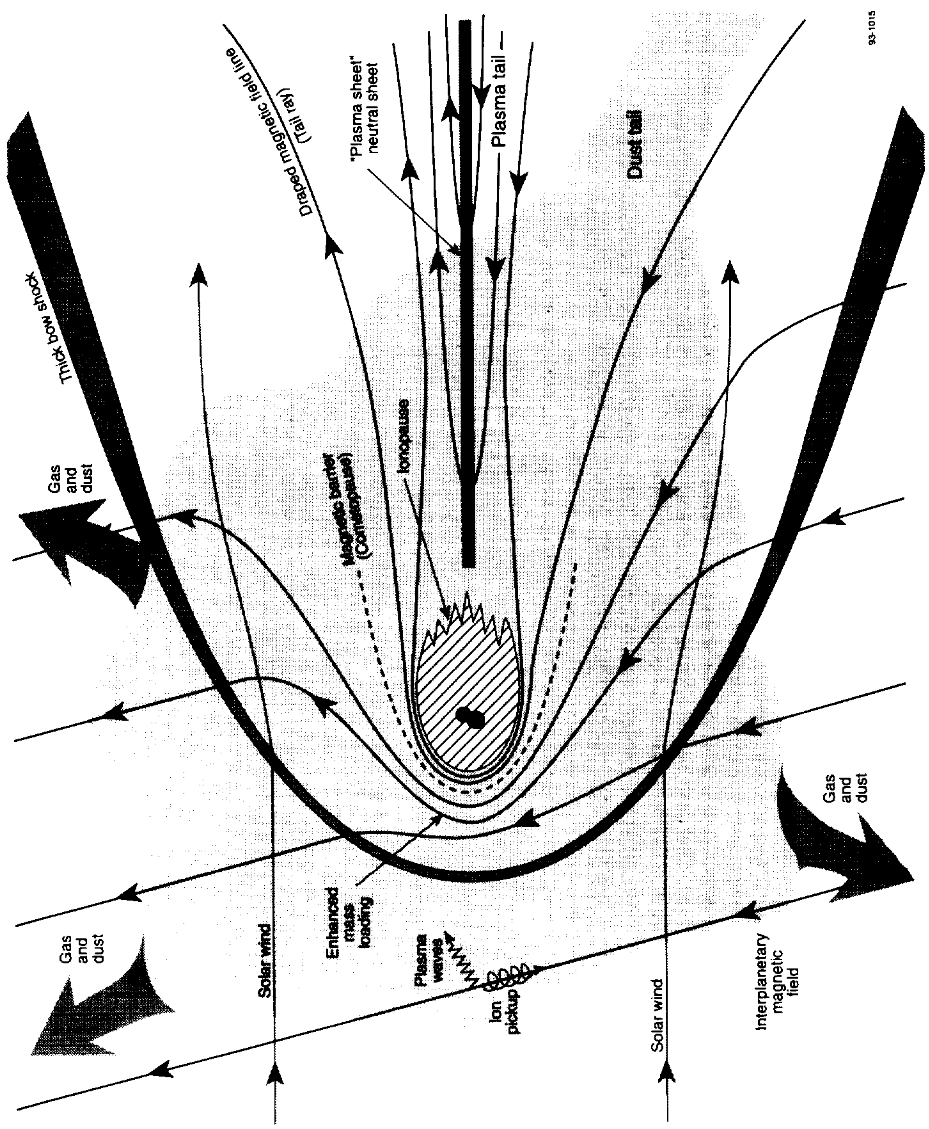
It is typical for the inner regions of Earth-like magnetospheres to contain dense populations of low-energy (e.g., 0.1- to 100-eV) plasmas. At Earth that

TABLE 4.4 Characteristics of Plasma Environments of Various Solar System Objects

Object	Configuration[a]	Size[b] (R_b)	Energy Source[c]	Plasma Source[c]	Embedded Material[d]	Aurora[e] (P/P_E)	Substorms	Radiation Belt[f] (I/I_E)	Radio Emission[g] (I/I_E)
Mercury	Intrinsic, ~aligned	1.5	Solar wind	Solar wind	—	?	Yes	? ?	?
Venus	Induced	1.15	Solar wind	Ionosphere	—	10^{-2}-10^{-1}	?	0 0	?
Earth	Intrinsic, ~aligned	10	Solar wind	Ionosphere, solar wind	—	1	Yes	1 1	1
Mars	?	1.15	Solar wind	?	Satellites?	?	?	? ?	?
Jupiter	Intrinsic, ~aligned	80	Rotation	Io	Gas, dust, satellites	10^4	?	1 10^2-10^3	20
Saturn	Intrinsic, aligned	20	Rotation/ solar wind	Satellites, rings, ionosphere	Dust, gas, satellites	10	?	10^{-3}-10^{-2} 10^{-2}-10^{-1}	3
Uranus	Intrinsic, large tilt	20	Solar wind/ rotation	Ionosphere	Dust, satellites	10	Yes?	10^{-2} 10^{-1}-1	0.1
Neptune	Intrinsic, large tilt/pole-on	30	Rotation	Triton, ionosphere	Dust, gas, satellites	10^{-1}	?	10^{-3} 10^{-3}-10^{-2}	0.5
Pluto	?	?	?	?	?	?	?	?	?
Comets	Induced	1000	Solar wind	Coma, solar wind	Dust, gas	?	Disconnection events	0	?
Asteroids	Remanent?	?	?	?	?	?	?	?	?

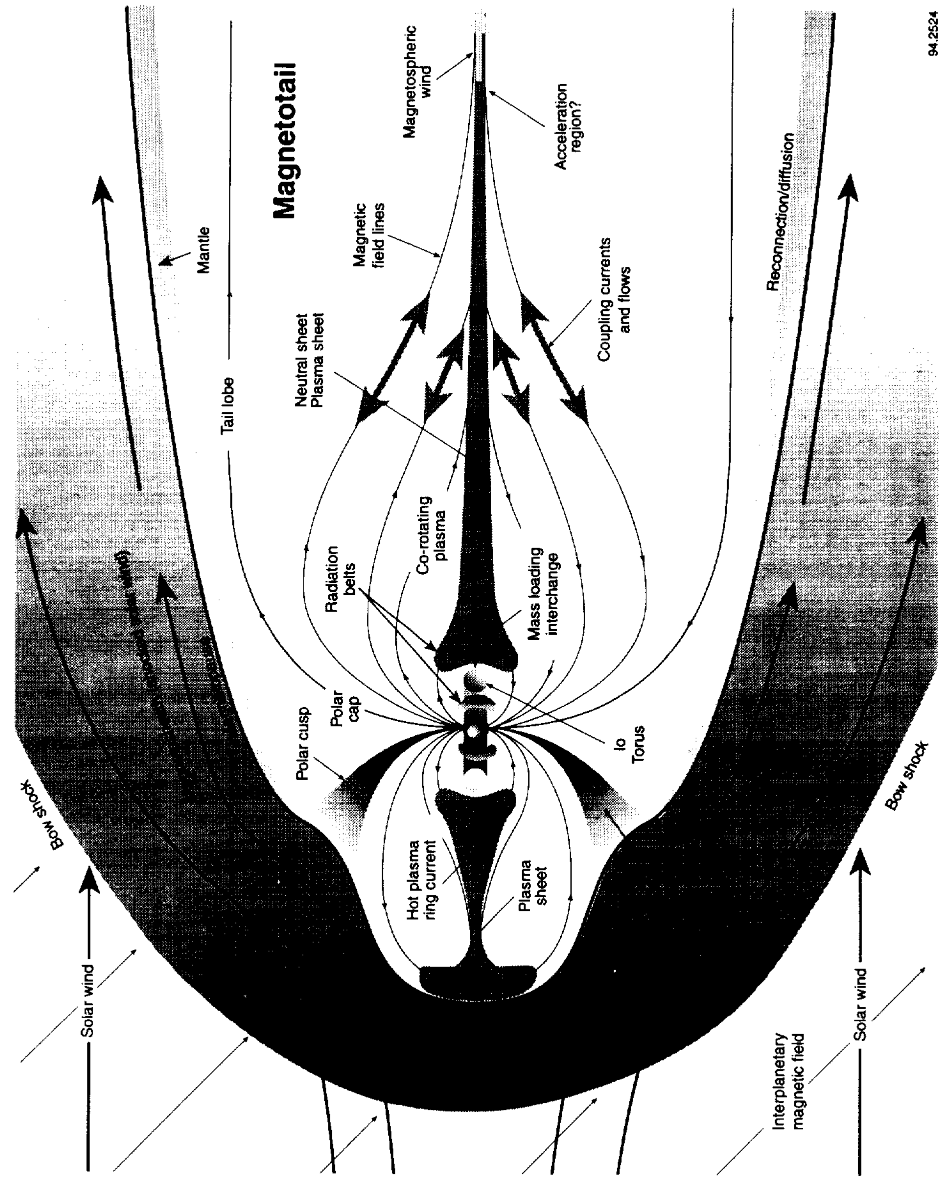
[a]The configuration can be either intrinsic (the internal magnetic field of the object is strong enough to stand-off the solar wind) or induced (the interplanetary magnetic field drapes over the object). The term "large tilt" means that the magnetic moment is substantially tilted ($\geq 25°$) with respect to the rotation axis of the planet, and that a "pole-on" magnetospheric configuration is expected for some rotation and orbital phases of the planet's motion.
[b]Sunward size of obstacle (magnetopause, ionopause). R_b is specified for the point of pressure balance between the solar wind and the internal fields or plasmas at the subsolar point; these sizes are scaled to the object's radius. Plasma disturbances may occur out to much larger distances.
[c]Represents an attempt to rank the strongest source for each object.
[d]Nonplasma occupants of the magnetosphere that may or may not act as plasma sources but that may interact in important ways with the magnetospheric plasma. For the outer planets, the term "dust" also includes the larger ring material obviously present in these magnetospheres.
[e]Ratio compares the total power P of the aurora with the corresponding value at Earth.
[f]Ratio compares the total intensity I with the corresponding value at Earth (E). Values are given for both ions and electrons at a few hundred keV.
[g]Ratio compares the total intensity I with the corresponding value at Earth (E). Values are the peak values in the spectrum of each planet.

NOTE: Question marks indicate that no proper measurements for the respective entry in the table have been made.



Thick bow shock
Draped magnetic field line
(Tail ray)
"Plasma sheet"
neutral sheet
Plasma tail
Dust tail
Gas
and
dust
Magnetic barrier
(Cometopause)
Ionopause
Enhanced
mass
loading
Solar wind
Plasma
waves
Ion
pickup
Interplanetary
magnetic
field
93-1015

FIGURE 4.6 Schematic of an induced cometary magnetosphere. The solar wind with its embedded magnetic field impinges on the comet's coma from the left. Ionization of the outflowing coma gases (primarily due to solar ultraviolet) causes "ion pickup" and the resulting "mass loading" of the magnetized plasma. The mass loading, in turn, causes the interplanetary magnetic field lines to drape over the cometary "ionopause." The buildup of magnetic field lines (increased field strength) close to the ionopause forms a "magnetic barrier" to the plasma flow. The solar wind flow is supersonic (with respect to several characteristic speeds in the plasma), and so a "bow shock" forms upstream of the barrier. The shock serves to slow the solar wind, heat it, and deflect the flow around the comet. The shock may not be distinct if mass loading far ahead of the comet slows the solar wind in a sufficiently gradual manner. The draped field lines form a "neutral sheet" of field lines with opposing polarities, supported by electric currents carried by energetic plasmas that form a "plasma sheet." The neutral sheet/plasma sheet structure forms the comet's "plasma tail," which is distinct from the "dust tail" (also shown). "Tail rays" are presumably ordered by magnetic field lines that have not completely "draped" into the tail. Plasma disturbances are produced at huge distances (10^6 km) upstream of the bow shock because neutral ionization and ion pickup occur over vast volumes.



Magnetotail
Magnetospheric wind
Acceleration region?
Magnetic field lines
Mantle
Tail lobe
Neutral sheet
Plasma sheet
Coupling currents and flows
Reconnection/diffusion
Co-rotating plasma
Radiation belts
Mass loading interchange
Polar cusp
Polar cap
Io
Torus
Bow shock
Hot plasma ring current
Plasma sheet
Solar wind
Interplanetary magnetic field
Bow shock
Solar wind
94.2524

FIGURE 4.7 Schematic of Jupiter's magnetosphere. Jupiter has been chosen as representative of "intrinsic" magnetospheres because of the wide variety of phenomena that are present in the system. The internal magnetic moment of Jupiter's magnetic field is oriented roughly perpendicular to the solar wind flow. The magnetized solar wind impinges on the planetary magnetic field from the left. A "magnetopause" forms, separating the planetary field regions from the solar wind field. The position of the magnetopause is established by balancing the solar wind pressure against the pressure internal to the magnetosphere. The solar wind flow is supersonic, and so a sharply defined bow shock forms upstream of the magnetopause. The innermost regions of such intrinsic magnetospheres contain the very energetic radiation belts, and they also typically include relatively dense populations of cool plasmas; at Jupiter the Io plasma torus plays that role as shown. Hot plasma typically dominates farther out, carrying the electric "ring current" that distorts the magnetic field away from its dipolar configuration. At Jupiter the distortions form a "magnetodisk" that merges into the "neutral sheet" of the "magnetotail," a wind-sock-like extension caused by the influence of the strongly blowing solar wind. This magnetotail extends at least 5 AU from Jupiter, beyond the orbit of Saturn.

population is called the "plasmasphere," a plasma reservoir in hydrostatic equilibrium with the planet's ionosphere. However, diversity between the different planetary magnetospheres results from the existence of different sources of cool plasmas. At Jupiter the dominant plasma source is Io, giving rise to the "Io plasma torus" represented in Figure 4.7. Outside of the cool, dense plasmas are regions in which hot (up to tens of keV) plasmas typically predominate. These plasma populations dominate in the sense that they carry the electric currents that substantially interact with (and distort) the planetary magnetic field. The associated electric current is called the "ring current." Cool populations can contribute to this ring current (within the "hot plasma" regions) via centrifugal effects on the rapidly rotating, dense populations. The result of the combined actions of these particle populations is the highly distended magnetic field. At Jupiter the distortions are extreme, forming what has been termed a "magnetodisk." A "magnetospheric wind," blowing away from Jupiter, apparently forms tailward of the magnetodisk.

Studies of Earth's magnetosphere have shown that strong global coupling from one region to another is a critical element as to how the system as a whole behaves. For example, as a result of the force transmitted by electric currents flowing along Earth's magnetic field lines, large-scale plasma motions in distant magnetospheric regions are mirrored in similar-scale motions of terrestrial ionospheric plasmas. Unfortunately, at other planets, little direct information is available about these coupling processes. For example, for the iogenic plasma near Jupiter to be accelerated to speeds approaching that of rigid corotation, forces must be transmitted along the magnetic fields from the high-latitude ionosphere. However, no in situ observations have been made in this latter region, and thus the ionospheric conductivities crucial to determining field line "slippage" can only be estimated, and the agents carrying the electric currents are a matter of conjecture. Broadband electrostatic waves have been detected in the jovian magnetosphere. Based on terrestrial analogies, these waves are associated with ion beams or currents flowing along important magnetospheric boundaries, such as the plasma sheet; thus, they are likely important indicators of, or participants in, a coupling process. Nevertheless, at present the extension of these ideas to all extraterrestrial magnetospheres is only speculation.

This general description raises a few questions. In no particular order, these are as follows:

- What is the nature of the solar-wind interactions with Mars and Pluto? Is Pluto's magnetosphere Venus-like or comet-like, or does the most distant planet have an intrinsic magnetic field? How do these interactions affect the state and evolution of the upper atmospheres and ionospheres of these two planets?
- How do the magnetospheres, and particularly the magnetotails, of Neptune and Uranus reconfigure themselves in response to their diurnal variations in orientation with respect to the solar wind (during the appropriate orbital epochs)?

- How does the configuration of cometary magnetospheres change in response to variations in the rate of ion pickup at comets due to varying heliocentric distance and time variations in the solar wind? Under what circumstances does a cometary bow shock exist?
- Why does Jupiter's middle magnetosphere have a neutral sheet configuration all around the planet (called a "magnetodisk"), whereas other magnetospheres have neutral sheets only within their magnetotails? Why doesn't Saturn have a magnetodisk?
- Does the magnetospheric wind at Jupiter extend across the magnetotail, and how is the wind related to the corotating magnetodisk?

SCIENTIFIC THEMES

Plasma and Energy Budgets

Earth's magnetosphere derives its plasma from the ionosphere and the solar wind. Several decades ago, the solar wind was believed to be the primary source; however, recent evidence has pointed to the ionosphere as the main supplier. A similar controversy concerns the outer planets. At Uranus and Neptune, for example, there is almost no evidence for a solar-wind source for internal plasmas, whereas at Jupiter the solar wind appears to be a contributor to the energetic particles. The relative strengths of the solar-wind and atmospheric sources of plasmas for different magnetospheric constituents are unresolved.

Within magnetospheres other than Earth's additional plasma sources are present and may dominate. For instance, satellites with atmospheres (or exospheres) are likely to be plasma sources for some intrinsic magnetospheres. A most notable case is Io, where the (poorly understood) interaction of magnetospheric plasma with the satellite's atmosphere produces an extended neutral "corona." Some of this coronal material is subsequently ionized (in excess of 10^{28} atoms per second) and "picked up" by the jovian magnetic field and energized by various processes, only some of which are understood to any quantitative degree. For all satellites with atmospheres (Titan at Saturn and Triton at Neptune), a torus of neutral gas should exist as a long-lived, but perhaps time-variable, reservoir of material. The icy moons and rings are also plasma sources arising through the action of sputtering (the process whereby energetic charged particles expel material through collisions with satellite surfaces). The plasma arising from sputtering is thought to be much weaker than the satellite atmosphere sources. At Uranus, for example, the uranian atmosphere appears to be the predominant supplier of plasmas, with the sputtered satellite and ring sources yielding at most minor contributions. However, at Saturn there is some question concerning the relative strengths of the contributions made by Titan's atmosphere (and torus) and the icy moons. At comets, the neutral gases from the coma and the solar wind both provide plasmas of significance to understanding the physics in these plasma environments.

The two primary sources of energy for magnetospheric processes, the solar wind and the rotation of the planet, seem to be common to all intrinsic planetary magnetospheres but have varying relative importance. Of the intrinsic magnetospheres, Earth's magnetosphere represents solar-wind-driven magnetospheres, whereas Jupiter is the prototype for the rotationally driven cases. The solar-wind coupling is an electromagnetic interaction; hence the solar wind can provide the energy for magnetospheric processes without necessarily providing the plasma. Thus, the magnetic field magnitude and orientation in the interplanetary environment are as crucial to the coupling as the solar-wind plasma density, temperature, and composition. The electromagnetic coupling drives electric currents and large-scale plasma motions (plasma "convection") within the interior of the solar-wind-driven intrinsic magnetospheres. Magnetospheric substorms are evidence of highly dynamic, solar-wind interactions for solar-wind-driven magnetospheres. The mechanism of solar-wind coupling has not yet been fully established. For example, the relative roles of magnetic-field-line reconnection and viscous interactions at the magnetopause have not been established with certainty.

The rotational energy source at Jupiter and other rotation-dominated magnetospheres (at Neptune and perhaps Saturn) depends on the planet's spin, its internal magnetic field strength, and ionospheric conductivities. The rotating neutral atmosphere enforces rotation of the ionosphere, and ultimately the magnetosphere, through collisions. The energy from the rotating magnetosphere can then be extracted by means of a number of mechanisms and can drive various magnetospheric processes. The degree to which the ionosphere can enforce the planetary rotation rate on the more distant regions of the magnetosphere is not established.

The mechanisms by which energy is converted to other forms (e.g., heated plasma) and transported from one region to another have also not been fully resolved. Some mix of the mechanisms identified in the section "Fundamental Plasma Processes" below is undoubtedly involved, but the determination of that mix will require substantial work with data from past and future missions. The classical problem in this area is to determine how energetic particles can be accelerated to the very high energies that are observed (tens of MeV).

The traditional discriminator between solar-wind predominance and rotational predominance for intrinsic magnetospheres is the ratio of the rotational electric field and the solar-wind electric field that penetrates into the magnetosphere. As an energy source, the solar wind is less important per unit volume at larger heliocentric distances (due to weaker solar-wind magnetic fields and lower solar-wind densities), but the greater cross-sections of the outer planets' magnetospheres partially compensate for this decrease. Studies of various radio emissions have indicated that the solar wind is an active participant in generating some signals, and so would appear to remain a source of energy at all planets. Even for Jupiter, where the rotational energy would seem to be dominant, some components of the radio spectrum correlate well with solar-wind conditions; even stronger correlations have been found for Saturn.

It is crucial to understand the input from the solar wind in order to understand the functioning of planetary magnetospheres. It follows that a fundamental understanding of the heliosphere's structure, evolution, and dynamics is important to the study of planetary magnetospheres (not to mention the importance of understanding the heliosphere and its origin in its own right). Instruments designed for planetary magnetospheric measurements have generally operated throughout the cruise phase of missions; the resultant measurements have provided the primary information about the solar wind (other than the information from observations made near 1 AU and those taken by the Helios and Ulysses missions). These observations of the interplanetary medium have led to a crude description of the heliospheric configuration, evolution, and fundamental processes near the ecliptic plane. In order to maintain this source of information, it is important to continue the relatively inexpensive practice of making cruise observations on planetary missions.[26]

The sinks of plasma and energy within Earth's magnetosphere are the atmosphere (e.g., auroral heating and precipitation), neutral-gas interactions within the magnetosphere (e.g., charge-exchange interactions), and the interplanetary environment (e.g., plasmas and energy that are sent down the magnetotail, leaking energetic particles). Within other intrinsic magnetospheres, satellites and rings can act as absorbers of plasma, both by direct impact and by providing neutral gases that serve as sinks. Clear-cut evidence of satellite- and, in some cases, ring-generated structure within energetic particle distributions has been observed at all of the giant planets; the details differ substantially from planet to planet.

Interest in satellites and rings goes well beyond their simple roles as sources and sinks of magnetospheric plasma. The interactions between the satellites and the magnetospheres are of interest in their own right. Jupiter and Io form the closest solar-system analogy to a binary star system in which one body interacts electromagnetically with its companion via the magnetic field to cause a wealth of magnetospheric phenomena. A critical aspect of this interaction is the occurrence of a large-scale, magnetic field-aligned current that connects Io with Jupiter's ionosphere, forming what has been termed an "Alfven wing" structure. This interaction has been recognized in Earth-based radio observations since shortly after the discovery of jovian radio emissions nearly four decades ago. The Saturn-Titan and Neptune-Triton interactions are similar to that of Jupiter and Io in nature and complexity, but such interactions may be progressively less important in their influence on the global magnetosphere. Electromagnetic interactions between magnetospheric plasmas and the icy moons of Saturn, Uranus, and Neptune are less evident in the data (beyond the satellites' actions as sinks when charged particles are directly encountered); hence, their role, if any, is largely unknown. Nevertheless, these more subtle interactions most likely include the production of pickup ions via sputtering and other processes.

Key Questions

Some key questions related to plasma and energy budgets include (in no particular order) the following:

- How important is the solar wind as a plasma source relative to other sources in planetary magnetospheres? Where is the solar-wind plasma in the magnetospheres of Uranus and Neptune?
- Why and how are radio emissions in rotationally dominated magnetospheres, such as those at Jupiter, Saturn, and Neptune, influenced by solar-wind input?
- How is iogenic plasma transported to Jupiter's middle and outer magnetosphere?
- How important is the solar wind in driving auroral and other processes at Saturn and Uranus? How does that importance vary as the orientation of Uranus's magnetic pole changes with respect to the solar wind?
- What is the relative importance of satellite atmospheres, satellite surfaces, rings, and planetary atmospheres as sources of material in planetary magnetospheres, and what is the disposition of these materials?

Auroral Processes and Magnetospheric Dynamics

Auroral emissions have been observed at all of the gas-giant planets, Venus, and, of course, Earth. However, the mechanisms of auroral generation within intrinsic magnetospheres apparently differ greatly from planet to planet. Auroral emissions result from processes that couple magnetospheric regions over great distances, and thus they are a fundamental diagnostic of global magnetospheric processes.

At Earth, solar-wind-driven, dynamical, substorm events cause the more intense auroral emissions, and the magnetotail is thought to have an important role in the energy conversion processes. As a result of the Earth example, a possible association between auroral processes and magnetospheric dynamics at other planets is strongly suspected, but it has not been verified. At Uranus, observed temporal variations within energetic particles suggest substorm processes. For purposes of comparing magnetospheres, it would be highly instructive to determine whether the observed ultraviolet auroral emissions are caused by dynamical substorm processes.

Very clear substorm signatures with time scales of minutes have been identified in various measurements of the particles and fields in Mercury's magnetosphere (versus time scales of hours for those at Earth). Our understanding of substorm processes would be greatly enhanced by determining whether optical emissions equivalent to auroral emissions are generated on Mercury's surface in response to these substorm events. It is crucial to ascertain the aurora-substorm association because Mercury has no classical ionosphere. At Earth, the ionosphere is a critical factor in substorm and auroral processes. Comparisons of substorms at Mercury and Earth, with their different time scales and ionospheres, would lead to improved models of solar wind interactions with magnetized planets.

At comets, plasma tail disconnection events have been likened to magnetospheric substorms. From a more general perspective, the plasma tails of comets show many dynamical features, including helical twists and filamentary structure. Because the cometary tails are visible, they offer unique opportunities to study the dynamics of magnetotails in general, provided the analogy between induced tails and the tails of intrinsic magnetospheres can be established. For example, the magnetotails of Earth and Uranus have been observed to "twist" in a fashion that may be analogous to what is observed at comets, and filamentary structure has been observed within the plasma sheet populations of the magnetotails of Earth, Uranus, and Neptune. The analogy between cometary magnetotails and other magnetotails needs to be established using in situ observations. With respect to substorms, the cometary tail disconnection events could become end members of the range of substorm phenomena, and hence an important constraint on substorm theory, once the analogy can be demonstrated.

Dynamical processes are not required for the generation of intense aurora. At Jupiter, for example, which has a total auroral power four orders of magnitude greater than Earth's, the approximately steady-state electromagnetic coupling between the magnetospheric plasma and the ionosphere may perhaps be responsible. At Jupiter, Saturn, and Uranus, an atmospheric emission called "electroglow" has been observed that apparently is another example of a glow generated more continuously via an entirely different, yet poorly understood, mechanism. Consequently, such glows are not strictly aurorae, but understanding their different origins is important to fully comprehending the full range of auroral emissions. To identify the cause of aurorae one generally must determine how auroral features map magnetically to distant magnetospheric regions. Available measurements of auroral luminosity generally have very poor spatial and temporal resolution, so that efforts to connect the emissions to various magnetospheric regions have been debatable. Recent Hubble Space Telescope images of jovian aurorae suggest that some progress can be made toward conclusive field-line mapping in the future, especially once the Galileo spacecraft is available to provide synoptic observations of the magnetosphere.

Radio emissions offer an important additional tool for diagnosing auroral processes. Each of the outer planets has rich radio emission spectra that were surveyed by Voyager. Virtually all of the observed magnetospheric radio emissions appear to be produced by either of two generation mechanisms. One of those mechanisms, the cyclotron maser instability, is known to operate in the terrestrial auroral zone, and it seems to account for the most intense emissions at each of the planets. Current understanding of the cyclotron maser instability allows the plasma environment near the source to be estimated, although Voyager made no in situ observations of any of the auroral radio emission sources. Radio emissions have not been detected from Mercury, but the Mariner Venus/Mercury (Mariner 10) spacecraft had no capability to measure these emissions. Moreover, the high solar-wind density and weak magnetic field at Mercury suggest that radio emissions generated in the magnetosphere could not escape the magnetospheric cavity, so that remote sensing of these waves would be precluded; hence in situ observations are even more important.

Key Questions

Some key questions pertaining to auroral processes and magnetospheric dynamics are (in no particular order) the following:

- What causes cometary tail disconnections? What is the relationship between tail disconnections and magnetospheric substorms? Given our ability to image the global structure of cometary plasma tails, what can we learn about magnetotail structure and dynamics in general from the study of comets?
- Does Jupiter's aurora result from plasma phenomena near Io's orbit, or is it driven by processes in the jovian magnetotail?
- Given that Mercury has a weak ionosphere at best and that terrestrial substorms apparently are highly dependent on ionospheric conductivity, how do substorms at Mercury relate to substorms at Earth? Does Mercury have auroral emissions?
- By analogy with what is thought to occur as a result of the Io-magnetosphere interaction at Jupiter, are aurora generated by the Triton-magnetosphere interactions at Neptune or the Titan-magnetosphere interactions at Saturn?
- Are the dynamical features observed at Uranus indicative of Earth-like substorms?
- Do substorms occur in rotationally driven magnetospheres? If so, do they occur more deeply down the magnetotails?
- What causes auroral emissions within induced magnetospheres like Venus's?
- Are there aurorae on Mars?
- To what degree can radio emissions be used in remote diagnostics of aurorae and their coupling to other magnetospheric regions?

Gas, Dust, and Surface Interactions with Plasmas

The physical processes governing the interactions of neutral gas, dust, and solid surfaces with magnetized plasmas are fundamental aspects of modern magnetospheric research. Energetic particles can modify material surfaces, and through this process the surfaces can in turn become sources of plasma and energetic particles. In the vicinity of rings, electromagnetic forces often dominate the dynamics of the smaller dust particles; accordingly, such forces must be taken into account in order to understand some features of the rings, such as the saturnian spokes, as well as the latitudinal distribution of dust in the highly asymmetric magnetic fields at Uranus and Neptune. Any momentum given to dust particles through these forces can be subsequently imparted to larger ring members via collisions. It has been suggested that some large-scale ring features result from such a process.

Gases and plasmas are intimately associated in many other locales. For example, the atmosphere of Titan and the neutral torus of Io are major plasma sources in the saturnian and jovian magnetospheres, respectively; nevertheless the mechanisms by which these are linked to the magnetospheric plasmas are understood only in a very rudimentary way. At the interfaces between the upper atmosphere, the ionosphere, and the magnetosphere, one finds regimes of complete collisional coupling between plasmas and neutral gases, regimes having various levels of partial coupling, and, at higher altitudes, regimes where these populations are fully decoupled. Plasma flow patterns of the magnetosphere drive neutral winds in the upper atmosphere with time delays that reflect the characteristics of the neutral gas/plasma coupling. Frictional heating results within both the plasma and neutral gas populations. Energetic particles couple magnetospheric processes to even deeper levels of the neutral atmosphere.

Comets are an excellent illustration of how the solar wind interacts with a body dominated by dust and gas. In some regions electromagnetic effects on the magnetized plasma can apparently dominate the dynamics and transport of the smaller dust particles. The electromagnetic configurations are controlled largely by the plasma/neutral gas interactions. The neutral gases of the coma are ionized in the solar wind (mostly by solar ultraviolet radiation) and, now charged, become tied to mass-loaded magnetic field lines. At comets (as well as in planetary magnetospheres with substantial satellite or ring sources of neutral gas), mass loading results from the ionization of neutrals in the presence of a magnetized plasma that is moving relative to the neutrals' rest frame. As particles become ionized, the newly created ions are accelerated by the motion of the induced electric fields, extracting the flow energy from the moving (solar wind) plasma and converting it to thermal energy. Depending on the mass being picked up, the moving plasma's flow can be reduced substantially. At comets, deceleration due to mass loading is responsible for the draping of field lines around the coma and the subsequent generation of tail rays and of the plasma tail itself. Perhaps the most amazing aspect of this interaction is the comet's great range of influence. Even in the upstream direction, the comet can disturb the solar wind to distances of millions of kilometers. The picked-up ions form anisotropic or "non-Maxwellian" distributions that can often drive various plasma wave instabilities. In return, the plasma waves further accelerate and heat the plasma.

As described in Chapter 3, the interaction of magnetic fields, neutral gas, and dust may have been very relevant to the evolution of the nebula from which the solar system formed.

Key Questions

Some key questions about gas, dust, and surface interactions with plasma include (in no particular order) the following:

- To what extent are energetic particles responsible for the modification (darkening) of satellite and ring particle surfaces?
- How do electromagnetic effects generate the spokes of Saturn's B-ring?
- Can electromagnetic effects produce noticeable structure within rings using dust particles as intermediaries?
- To what extent, and how, do energetic particles modify the chemistry of upper atmospheres?
- How does the solar wind interaction with Pluto affect its upper atmosphere and ionosphere?
- How is plasma extracted from the atmospheres of Io, Titan, and Triton?
- To what extent do plasma effects determine the behavior of dust and gas within cometary comae?

Fundamental Plasma Processes

Planetary magnetospheric systems are studied in order to establish how specific inputs caused observed outcomes. These causal links are fundamental plasma processes with wide application to many other astrophysical situations. As noted, planetary magnetospheres can be characterized by a number of key parameters (e.g., planetary magnetic moment, external solar-wind conditions, the presence of embedded plasma sources and sinks such as satellites, and so on). These quantities determine magnetospheric behaviors (e.g., the occurrence and strength of substorms, the intensity and character of aurora, the nature of radio wave emissions, and the presence of radiation belts; see Table 4.4).

Some of the basic plasma processes that are important in the workings of magnetospheres include (1) reconnection, one of the schemes by which magnetic energies are converted to other forms of energy; (2) the pickup process whereby particles become ionized and are attached to field lines; (3) magnetic field-aligned currents as global coupling agents; (4) the formation of shocks, neutral sheets, and other types of sudden transitions in collisionless media; (5) the physics of dusty plasmas; (6) field-line draping and Alfven wing formation; (7) viscous interactions in collisionless media; (8) critical ionization phenomena in classically collisionless media (ionization resulting from the fast motion of neutral gases with respect to magnetized plasmas); (9) plasma-materials interactions, including sheath formation; (10) magnetohydrodynamic phenomena; (11) wave-particle interactions that allow energy to be exchanged between electromagnetic waves and charged particles; (12) diffusive transport of charged particles; and (13) collision-induced processes such as ionization and line emission in dense plasmas.

The wave-particle interaction is the best studied of the fundamental processes listed, and it is a unifying aspect for many of the other processes mentioned (e.g., reconnection requires a dissipation mechanism that is probably supplied by wave-particle interactions). These interactions have been observed for a majority of the explored solar system bodies, including the outer planets, Venus, and comets. Interestingly, virtually all plasma waves detected near other planets have clear terrestrial analogs. Accordingly, a good start on the theoretical understanding of these waves, including the wave-particle interactions associated with them, is in hand.

Many wave instabilities observed in the Io torus are clearly intense enough to precipitate energetic electrons and ions into the jovian atmosphere and thereby to excite aurorae; nevertheless it is not yet certain that these can fully account for the some 10^{14} W of precipitated energy required to explain the ultraviolet auroral emissions observed by Voyager. Whistler-mode emissions at Uranus are also sufficiently intense to drive strong electron diffusion, and hence the precipitation there, although it is not obvious that the electrons can be replenished at a sufficient rate to explain these observations. It is not understood why Neptune's wave spectrum is extremely weak compared to those of the other planets; perhaps Voyager's unique flyby trajectory at Neptune simply missed some of the more important regions. The Pioneer Venus orbiter provided the most extensive (in both time and spatial coverage) set of wave measurements for any planet except Earth, but only four frequency channels were available. Thus, many unanswered questions and various controversies remain.

Beginning with the International Cometary Explorer's observations at Giacobini-Zinner, plasma waves have been held as very important intermediaries in the interaction of the solar wind with comets. Various waves are driven by the pickup ions, and the region of space surrounding the comet that exhibits this wave activity is enormous. It seems clear that plasma waves play an important role in converting the bulk energy of flowing plasmas into heat and hence are important in the energy budget of a comet.

Key Questions

Some key questions concerning fundamental plasma physics include (in no particular order) the following:

- How are magnetospheric plasmas accelerated to the observed high (tens of MeV) energies?

- How do charged dust grains bind in the presence of a magnetized plasma? This question is especially relevant with respect to origins.
- What is the role of plasma waves in the heating and acceleration of cometary ions?
- What are the dominant processes that couple flowing neutral gases and magnetized plasmas? Applications for this general question include comets and magnetosphere-ionosphere-atmosphere coupling.
- What provides dissipation in a collisionless plasma? This question is relevant to such processes as bow-shock formation, magnetic field-line reconnection, and viscous interactions at the magnetopause.
- What limits the current-carrying capability of a plasma? The answer to this question is relevant to auroral processes, the occurrence of substorms, and Io-Jupiter interactions.

OBJECTIVES

The following objectives, while inevitably incomplete, are a representative set as suggested by the current state of knowledge in the early 1990s. In no particular order, they are as follows:

- Determine how, and the degree to which, plasmas and electromagnetic environments affect planetary gas (including the atmosphere), dust, and solid surfaces. At issue are the degree and nature of coupling between plasmas, neutral gases, and dust in various settings. The effects of energetic particles on surfaces and atmospheric chemistry and outflow are also involved. Comets and the saturnian and jovian systems are principal locales for studying some of these issues.
- Understand how solar-wind and planetary variations drive magnetospheric dynamics, including substorms, for various magnetospheric conditions. Planetary variations include changes of such diverse aspects as the volcanic activity of Io at Jupiter, the internal magnetic orientations of Uranus and Neptune, and the outgassing from comets. A prerequisite for this objective is to understand the solar wind and its temporal and spatial variations. Therefore, a continuation of the cost-effective practice of including solar wind observations during the cruise phase of planetary missions is a primary method for achieving this objective. A better inventory of the occurrence of substorms at the different planets is needed. Orbital missions, or other ways of achieving long-term monitoring, will be required. In addition to being able to observe the auroral luminosity, it is necessary to make in situ measurements of the plasmas and waves connected to the auroral zones in order to determine the causative processes. Mercury, Uranus, and Jupiter are prime targets for addressing this objective.
- Determine the roles of microscopic plasma processes in the mass and energy budgets of planetary magnetospheres, and ascertain the energy conver-

sion processes that yield auroral emissions. The issue here is to determine the degree to which large-scale processes are regulated by localized fundamental processes. For example, plasma instabilities can limit the current-carrying capability of a plasma; wave-particle interactions could be responsible for the precipitation of energetic charged particles into the atmosphere that causes some aurorae; and shock waves can accelerate particles to high energies. Aurorae provide fundamental diagnostics of the coupling of different magnetospheric regions over global scales, and thus understanding how they are generated is of particular interest. Jupiter, Uranus, Neptune, and comets are appropriate places to address this issue.

• Discover how differing plasma sources and sinks, energy sources, magnetic field configurations, and coupling processes determine the characteristics of both intrinsic and induced planetary magnetospheres. This question expresses the essence of many magnetospheric physicists' interest in planetary research. Nature has provided a vast array of differing magnetospheric conditions: strongly magnetized and unmagnetized bodies, rapidly rotating and slowly spinning bodies, aligned and nonaligned magnetic moments, magnetospheres with embedded satellites and those without, satellites with atmospheres and those without, atmospheres with high and low levels of outflow, and so on. The outcomes of these many magnetospheric experiments truly offer the prospect of developing a "first-principles" understanding of magnetospheric processes in particular and of astrophysical plasma processes in general.

• Determine what studies of contemporary planetary magnetospheres tell us about processes involved in the formation of the solar system. Pertinent here is the hypothesized role of plasma and electromagnetic effects in modulating the evolution of the solar nebula and the formation of the solar system via interactions between plasma and dust (possibly affecting the ability of dust particles to aggregate and form planetesimals) and plasma/neutral gas interactions (possibly affecting the collapse of molecular clouds). Studies of planetary magnetospheres, including comets, will clearly refine the understanding of these basic interactions. Nevertheless, the relevance of such interactions to solar system origins remains to be established. Prime targets for addressing this objective are comets, Jupiter, and Saturn. Comets, and to some extent Saturn, provide our best laboratories within which to study the electromagnetic effects on dust. Jupiter (because of the strong Io torus interaction) is of interest because of the potential for understanding the role of magnetic fields in the transfer and redistribution of angular momentum within plasma/gas systems, an issue of relevance to the collapse of molecular clouds to form protostars.

• Characterize the plasma environments and the solar wind interactions of Pluto-Charon and Mars. This objective is motivated by an interest in completing the exploration of solar system magnetospheres; it does not necessarily reflect the overall scientific importance of studies of Pluto and Mars over other issues. Simply determining whether there is a substantial magnetic field at Pluto or whether the solar wind interaction with Pluto is Venus-like or comet-like will provide an important aspect to Pluto's atmospheric model, constraining the range of atmospheric outflow and upper-atmospheric heating.

WHAT TO STUDY AND WHERE TO GO

Given the wide range of magnetospheric issues and plasma environments in the solar system, it is simple to conclude that a complete program of research could easily incorporate any and all of the planets, comets, asteroids, and the solar wind itself. However, such a program is not possible, even with robust funding of planetary research. In times of budgetary constraints, it is even more clear that progress must be made in the most efficient way possible. While there are many ways to ensure efficiency, one is to target those environments that offer broad, rich fields of study, or that offer unique opportunities to make significant progress on one or more objectives. Below is a list of plasma environments that meet such criteria. They are given roughly in descending order of priority based on the objectives described in the previous section. This list should not be viewed as exclusive since, particularly for highly focused studies, other targets might yield high-priority objectives as discussed in detail above.

Jupiter and Saturn

In this prioritization, COMPLEX has assumed that the Galileo mission to Jupiter and the Cassini mission to Saturn will both be successfully executed. But it is important to remember that Galileo will remain very close to the equatorial plane, completely missing high latitudes that are essential to studies of aurorae, substorms, and magnetospheric coupling. (Ulysses skirted these high latitudes, and its tantalizing observations confirm the notion that high-latitude studies at Jupiter are important.) Also the crucial Io region will be only minimally sampled.

In a 1986 report, COMPLEX made similar statements about the status of our understanding of the jovian system after the successful completion of the Galileo and Ulysses missions.[27] That report went into much greater detail than appears here on the importance of the inner jovian magnetosphere and the desirability of visiting high latitudes to gain a more thorough understanding of the jovian magnetosphere. COMPLEX further points out that while a very complete survey of the equatorial magnetosphere will be completed by Galileo, the restricted data rate that Galileo will achieve will result in virtually none of the high-resolution (in terms of time, spectrum, energy, and so on) measurements that are important in many of the objectives listed above. The advanced fields and particles instrumentation on Cassini and the provision of a wide range of orbital inclination promise to enable coverage of the primary magnetospheric objectives at Saturn.[28]

Just as Earth's magnetosphere is a prototypical solar-wind-driven magnetosphere, so is Jupiter's *the* prototypical rotationally driven magnetosphere. Thus, from a comparative perspective, Jupiter holds a special place. In addition, there is no magnetosphere in the solar system that can rival Jupiter's in terms of energy, plasma production, or complexity. Even within this prototypical system where rotational energy is predominant, important solar-wind influences are also evident. The Io-magnetosphere interaction provides a primary case for plasma/neutral gas interactions. Mass loading considerations and chemistry play roles similar in importance to the physics of magnetized plasmas. Other than the specific objective of completing the exploration of the solar system by characterizing the solar wind interactions with Pluto and Mars, all of the objectives listed in the previous section can be pursued within Jupiter's magnetosphere.

Comets

The three comets observed briefly to date have only reinforced the notion that these objects are very important to the understanding of plasma physical processes in the solar system. Most importantly, comets are ideal laboratories for studying the interactions of gas and dust within a magnetized plasma. The cometary environment is the most obvious locale for which to develop models of these interactions that can be applied to the theory of solar system formation, including gas, dust, and plasma interactions. The most useful studies would be performed by extended observations in order to help sort out spatial and temporal variations, for the purpose of allowing comparisons of various aspects of the interactions at different levels of cometary activity and over varying solar wind input conditions.

Mercury

It has been recognized since Mariner 10's observations of Mercury's substorm-related phenomena that Mercury would be an ideal magnetosphere within which to study substorms. The time scales for substorms at Mercury are of the order of minutes, offering a significant difference from the hour-long scales at Earth. Theories constructed for terrestrial substorms rely critically on the ionospheric conductivity; with only a weak ionosphere at Mercury, a severe but illuminating test for substorm theory could be carried out. In a previous report, COMPLEX stated that the "determination of the structure and time variation of [Mercury's] magnetic field should be elevated . . . to a primary objective."[29]

Pluto

Pluto provides a unique venue to study solar wind interaction of a drastically different nature in the distant solar wind. Regardless of the type of interaction, the Pluto/solar wind interaction would be a new and different case for comparison with others. Even if Pluto has a substantial magnetosphere, it would be significantly different from those of the gas-giant planets because of Pluto's size and weak atmosphere. If the interaction were either Venus-like or comet-like, the great heliocentric distance would provide a contrast to the previously studied induced magnetospheres.

Neptune, Uranus, and Mars

In priority order, the objects Neptune, Uranus, and Mars are additional targets that have substantial potential for returning valuable information concerning magnetospheric processes. Neptune and Uranus change their magnetic configurations diurnally (at least during certain seasons), and it is important to study intensively the structure and dynamics of these magnetospheres.[30] The interaction between Triton and Neptune's magnetosphere or Triton and the solar wind is of substantial interest, and the possible substorm-aurora connection at Uranus needs to be resolved. At Mars, it is important to gain a first-order understanding of how the solar wind interacts with this planet and to begin the study of martian aeronomy.[31]

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5

Basic Science and Infrastructure

While spaceflight programs have been NASA's primary focus since its inception, space probes are not the only source of the rich harvest of information about the planets gathered during the last three decades. Equally important contributions have been made by ground- and space-based observatories, laboratory analysis and experiment, and theoretical modeling. Sustained and even expanded support for these efforts is needed if they are to continue providing the solid foundation of knowledge necessary for maintaining the spectacular success of planetary missions.

A complete strategy for the scientific exploration of our solar system must surely include the rationale for undertaking particular planetary missions, as described elsewhere in this report. But, in addition, it must also contain an understanding of the role played by the two other necessary components of a successful program: individual scientists—principal investigators—pursuing their own research projects, and quality facilities for performing research and making remote observations. This broad-based planetary research is conducted by researchers in universities, nonprofit laboratories, and NASA centers across the country, and is largely supported through NASA's research and analysis (R&A) programs. These programs maintain the breadth of research activity necessary to properly digest and correlate the information returned to us by planetary spacecraft; they also allow the efficient planning of future missions by introducing new ideas, raising essential questions, and developing new instrumentation.

Major advances in fundamental research occur sporadically—basic science generally does not follow a preconceived path. It would be folly to try to prioritize the research directions of the entire community of planetary scientists. The provision of stable, adequate funding and state-of-the-art research facilities, however, coupled with the relentless efforts of highly qualified scientists, ensures the type of steady progress in basic research that leads to conceptual breakthroughs and major advances in knowledge.

RESEARCH AND ANALYSIS

Research and analysis funding supports the efforts of individual scientists (whether in academic institutions, federal laboratories, nonprofit institutions, or industrial corporations) and their assistants and students, as well as telescopic instrumentation, laboratory equipment, and hardware development. These researchers and facilities attack a range of problems through analysis of spacecraft data, complementary theoretical studies, fundamental laboratory investigations in physics and chemistry, ground-based observational campaigns, and so on. R&A funding supports researchers who work on planetary science topics not necessarily associated with particular space missions.

These studies include, for example, telescopic observations of distant Pluto and Charon; analyses of minute interstellar grains predating the birth of the solar system; computer simulations to learn planetary orbital histories half-way back to the beginning of time; reexamination of archival data long after spacecraft missions end to reveal the inner turmoil in Jupiter's Great Red Spot; and surveys of the minor planets to show that these objects cluster into a few classes. The R&A program has produced many surprising findings and fundamental insights.

R&A programs are thus an essential link in the chain of evidence needed to achieve a full understanding of the scientific problems that arise from planetary exploration. The major discoveries of space missions would stand largely as unconnected facts without the solar system-wide backdrop provided by the studies supported by the R&A programs. R&A programs are thus the heart of the planetary exploration effort. Indeed the argument can be made that, in this new era of detailed exploration, data analysis is essential both before and after the missions themselves. Without analysis before missions fly, researchers do not know which are the important questions to address or which instruments are most likely to provide the most useful data; without analysis following the missions, one has merely obtained strings of numbers and pretty pictures, but little real knowledge. An excellent example of the value of R&A funding is provided by our current information on origins (Chapter 3): almost all this information comes from various facets of the R&A program (observations of star-forming regions, laboratory studies of meteorites, numerical modeling of aggregating planets, theoretical studies of cosmochemistry, and other such efforts).

These funds not only provide depth and breadth to planetary research, but they also train many individuals, both graduate students and postdoctoral fellows, who often serve their "apprenticeships" in small groups under the direction of senior scientists. Some of these junior partners will become the next generation of our nation's planetary explorers, while others will move into diverse technological fields after having been drawn into science by the excitement of planetary research.

COMPLEX is not alone in emphasizing the importance of individual research for astronomical studies. The National Research Council's Astronomy and Astrophysics Survey Committee—the Bahcall Committee—declared in 1991 that:[1]

> The highest priority of the survey committee for ground-based astronomy is the strengthening of the infrastructure for research, that is, increased support for individual research grants and for the maintenance and refurbishment of existing frontier equipment at the national observatories.

While this recommendation was directed primarily at the National Science Foundation (NSF), similar remarks apply to NASA's R&A programs in planetary science. For more than a decade, recurring annual cost overruns in the flight programs have been absorbed to some degree by reducing R&A support. In the long term, such "solutions" are short-sighted.

Reports by internal NASA committees have identified several disturbing aspects of the R&A funding issue:[2]

> The steady decline in Research and Analysis support has resulted in the failure to analyze and publish large amounts of planetary data acquired with expensive space missions. . . .
>
> The decline in size of individual research grants to university and NASA center investigators has resulted in a proliferation of proposals; often a university researcher or one working at the Jet Propulsion Laboratory must seek support from five or more programs in order to cover his or her salary plus modest research funds. The greatly increased number of proposals, plus expanded procedures for their review and evaluation, has a significant, negative impact on the amount of time a scientist has to perform the work for which he or she is supported.

The general theme—that small amounts of additional funding can substantially increase the scientific yield of major missions—is also true for mission operations. Even following launch, missions can be seriously hampered unless sufficient funds are provided to run engineering tests, to properly develop instrument sequences, to stimulate interdisciplinary research, and to take advantage of scientific opportunities for cruise science (measurements of the interplanetary environment) or secondary targets (e.g., other planets or asteroids).

FACILITIES

Laboratories

The status of the analytical facilities used for extraterrestrial materials research was reviewed in 1988 by NASA's Planetary Materials and Geochemistry

Working Group. Although such facilities do not constitute the whole of the laboratory infrastructure of planetary science, the needs and problems associated with them may be taken as representative of those of the wider community. The following conclusions from the working group's 1988 report are therefore believed to be applicable to the planetary-science laboratory infrastructure as a whole:[3]

> From the Agency point of view, advanced facilities are necessary to accomplish NASA sample-return mission objectives as well as those for planetary materials. These facilities should be regarded as flight instruments for the sample-return missions. . . .
>
> The analytical techniques presently used by the Planetary Materials and Geochemistry Program will continue to produce excellent science. This core program must continue to be supported; however, it needs to be both upgraded and supplemented with advanced techniques. . . .
>
> A significant fraction (approximately half) of the analytical instruments utilized by Program [principal investigators] are of pre-1980 vintage; some are much older. . . .
>
> Upgrading is necessary because, due to funding limitations in the past decade [1978-1988], there has been a slow and steady erosion in program analytical capabilities relative to state-of-the-art laboratories, e.g., in the major European geochemistry research institutes. . . .
>
> Given the history of level program funding and the need to upgrade present Program capabilities, development of advanced instrumentation requires supplemental funding.

In response to the working group's report, NASA established a new program, the Planetary Instrument Upgrade Program (PIUP). In FY 1992, $2.5 million was appropriated for the upgrade of analytical instrumentation used to study planetary materials and geochemistry. However, PIUP funds were deleted from the FY 1993 budget, so that the present situation is only marginally improved over that described in 1988. The comments of the working group remain pertinent today. During the past few years, considerable development has taken place abroad and in other research disciplines in the crucial area of microanalytical techniques. Most such development in the United States, however, has occurred in the private sector and is rarely available to public-sector investigators.

In addition to analytical instrumentation, experimental studies, such as those that simulate natural systems or generate baseline data, play an important role in planetary research. Examples of the former include experimental petrology and numerical, hydrodynamical code simulations of cratering; examples of the latter include determinations of equations of state and other physical and chemical properties (e.g., opacity, spectral signatures) of planetary materials under relevant ambient conditions of temperature and pressure. Such studies are required to thoroughly understand spacecraft observations. Adequate support of this work is necessary to optimize the scientific return from planetary missions.

Ground-Based and Earth-Orbiting Telescopes

NASA has supported several major ground-based and Earth-orbiting telescopes that have provided planetary measurements that would be impractical, if not impossible, to obtain from spacecraft missions. The Infrared Telescope Facility on Mauna Kea provides nearly diffraction-limited images of solar system objects, even to the point of discerning the eruptions of individual volcanic hot spots on Io. The Kuiper Airborne Observatory, besides obtaining much of the available infrared spectroscopy of planets and satellites and star-forming regions, has provided a mobile platform for occultation measurements, which are observable only at localized spots on Earth. The Hubble Space Telescope allows planetary scientists to image the atmospheres of the giant planets at a resolution equal to that of the Voyager spacecraft approach sequences. The International Ultraviolet Explorer has traced the spatial distribution of many important cometary constituents and has probed the atmospheres of the planets. The Infrared Astronomical Satellite has yielded fundamental insights about the interplanetary dust complex and has revealed the presence of possible planet-forming disks around newly formed stars.

In addition to these major instruments, other telescopes have been useful for certain observations—particularly monitoring programs and survey work. For example, relatively small telescopes on Kitt Peak and Palomar Mountain are equipped with sensitive detectors to undertake searches for comets and asteroids with Earth-crossing orbits. Modest-size telescopes at Steward Observatory, McDonald Observatory, Allegheny Observatory, and elsewhere have permitted the long-term observational programs needed to seek planetary companions of nearby stars. The "planetary patrol," operated by Lowell Observatory for many years, has provided unique meteorological records for Mars, Jupiter, and Saturn.

No less important than the telescopes themselves are the instruments placed at their focal planes. Recent advances in array detectors—particularly those operating in the infrared—have yet to be fully realized in telescopic instruments, both on the ground and in orbit. Infrared wavelengths have particular significance to planetary astronomy, since they cover the thermal energy range of virtually all solar system bodies. In addition, many important species have spectral signatures in this portion of the spectrum. Large-format cameras, as well as medium- and high-resolution infrared spectrographs, have a special importance to planetary science.

The Bahcall report presented the consensus recommendation of the astronomical community for future initiatives concerning observing facilities, most of which would appreciably benefit planetary science. All four of the most highly rated major facilities (the Space Infrared Telescope Facility, an infrared-optimized 8-meter telescope, the Millimeter Array, and a Southern Hemisphere

8-meter telescope) would be extremely valuable for studying planets in our solar system or for scrutinizing the births of other planetary systems in nearby regions of star formation. Many of the moderate program elements recommended in the Bahcall report—such as adaptive optics, the Stratospheric Observatory for Infrared Astronomy, optical and infrared interferometers, and the Astrometic Interferometry Mission—would be similarly useful.[4]

The Astrometric Interferometry Mission, as proposed in the Bahcall report, is similar to proposals by NASA's Toward Other Planetary Systems Science Working Group (TOPSSWG), whose 1992 report advocated a three-step program directed toward the detection and study of extrasolar planets and protoplanetary disks.[5] Starting with the proposed NASA participation in the Keck II telescope (as well as a continuation of ongoing and new ground-based efforts), TOPSSWG's report (building on an earlier COMPLEX report[6]) argues that an Earth-orbital telescope should be developed to search for other planetary systems, through either astrometric or direct imaging techniques. If successful, the final step would be the construction of a long baseline array of interferometric telescopes to search for and characterize Earth-like planets—a goal that might require instruments in space or even on the lunar surface.

Computation

Theoretical modeling of complex physical phenomena has advanced to the stage that multidimensional representations are now commonplace. This development potentially permits synergy between theoretical models and observations of the physical system that the models are supposed to represent. As long as studies were restricted to one-dimensional models of atmospheres, for example, there was little hope of fully understanding a complicated three-dimensional structure like Jupiter's Great Red Spot.

The development of extremely powerful computers was a necessary antecedent to the broad advance in theory taking place today. Data processing and, especially, large-format images taken in several wavelengths, require similarly fast machine speeds and extensive memories, and so there is a fairly widespread need in planetary science for access to significant amounts of computational power.

Two contrasting options exist for individual scientists who require affordable computer power: supercomputers and workstations. Supercomputers are expensive (around $10 million each), but access to them at NSF or NASA centers is provided at no cost to the investigator. At the other end of the scale, powerful, though relatively inexpensive, workstations are often dedicated to the use of a single scientist and may very well yield more computational cycles per year than an investigator is likely to receive at a supercomputer center.

NASA recently recognized the growing importance and cost-effectiveness of workstation-class machines through its creation of the Computational Upgrade Initiative, which specifically sought to provide fast workstations to planetary scientists with computationally intensive tasks. Unfortunately, the initiative was funded only in NASA's FY 1992 budget.

Because supercomputers may be approaching practical limits on the speed of individual processors, further rapid growth in the power of supercomputer-class machines is most likely to result from the continued development of massively parallel machines (MPMs), in which many processors are linked together to solve problems. The High Performance Computing and Communications Initiative is a national program intended to provide greatly increased computational speeds and data transmission rates, the former primarily through the development of MPMs.

Massively parallel computers offer the possibility of achieving multiple power-of-ten increases in speed over the present generation of supercomputers, and, once available, will be valuable in exploring various planetary problems, provided that algorithms can be developed that exploit the capabilities of MPMs. Higher data transmission speeds will undoubtedly aid in the sharing of data that often characterizes the collaborations arising in contemporary planetary science.

SPACE TECHNOLOGY

While specific flight missions sometimes have their own instrument development programs, NASA has recognized for some time that an ongoing program is needed to support engineering research into a broad spectrum of instrument technologies that might be critical for future flight missions. In the Solar System Exploration Division, for example, this role is performed by the Planetary Instrument Definition and Development Program. While modest, this program has already provided the seed money for developing a number of potentially important instruments for future spaceflight.

The next stage of planetary exploration will probably involve missions based on lightweight spacecraft and launch vehicles (e.g., Mars Pathfinder and Discovery missions) and small landers (such as those proposed for the Mars Surveyor program). As the solar system exploration program for many planetary objects moves beyond reconnaissance and into a phase of detailed study, sample-return missions are more likely to be needed. All of these missions place an increasing demand on the technology of small-scale sophisticated instruments. Further, detector technology (at all wavelengths) continues to advance, often driven by national security needs. Cooling requirements for new sensors are no longer, in all cases, as demanding as in the past. And, where cooling is required, lightweight cryocoolers, originally developed for military applications, are now available. There is, therefore, a real opportunity to introduce a new generation of flight instrumentation that is significantly more advanced and often less demanding in terms of mass and power requirements. Considering that previously classified instruments and components have recently become available as security restrictions have eased, the planetary community needs to take advantage of these opportunities, especially on Discovery missions.[7] More comprehensive missions will need to develop their own instruments.

A recent NASA study on the expenses associated with planetary flight instruments recommended that 6% to 8% of the final instrument cost, on average, be expended in instrument development prior to the confirmation of a mission's scientific payload.[8] These funds would be devoted to ensuring that the difficulties and costs of producing a final flight instrument are realistically assessed before NASA becomes committed to a particular instrument. COMPLEX supports this approach to instrument development; in the long run it should be more cost-effective.

The Joint Committee on Space Science Technology Planning of the Space Studies Board and the Aeronautics and Space Engineering Board studied the effectiveness of NASA's Office of Aeronautics and Space Technology (OAST) in developing technology for NASA's former Office of Space Science and Applications (OSSA).[9] The committee found that OAST's integrated technology plan was a "good first step" but that NASA had not yet found a means for "gathering, evaluating, and selecting possible technology development projects comparable to the systematic means it has used for scientific experiments for the last 30 years" (p. 50). OSSA's Solar System Exploration Division was chastised for not doing a better job at establishing its technology needs and acting to address those needs. Among other recommendations, the committee stated that "NASA should act to broaden the foundation of its research base by increasing the direct involvement of university research laboratories in the development of technology for space science" (p. 54). The committee also found that "designing missions to be 'faster, better, and cheaper' has the potential to improve NASA's performance in developing new technology for space science and should be put to the test in cases where significant scientific objectives can be met by spacecraft built on these principles" (p. 53). To the extent that the requirements for achieving first-class space science can help drive technological development, both NASA's space science and the nation's technological prowess will benefit.

It is also important that adequate launch capabilities be available. Major mission objectives can be severely compromised by mass and power limitations brought about by low launch energies. Over the years space engineers have become remarkably proficient at using close flybys of various celestial bodies to gravitationally redirect spacecraft, thereby saving substantial launch energy. Such feats, however, often increase flight times and bring the spacecraft closer to the Sun than would otherwise be necessary, requiring additional thermal protection.

MIX OF MISSION SIZES

To date, the solar system has been explored in various ways, ranging from the late-evening, unsupported research of dedicated amateurs in their backyard observatories to the multibillion-dollar Apollo armada that visited the Moon a quarter century ago. Each of these approaches has its own virtues and drawbacks. An individual researcher can quickly change direction or pursue "crazy" ideas, but obviously is not capable of conducting continual multiinstrument observational campaigns or of taking on complex technological challenges like returning samples of the jovian atmosphere. "Crazy" ideas may overturn the ruling hypothesis of the day. Revolutions in understanding have also arisen as a result of essentially all large flight programs, from Apollo and Mariner 9 through Voyager to Magellan. While major missions may generate much of the underlying information that drives planetary science, such large undertakings must move slowly and cautiously; furthermore, large missions can, by economic necessity, be focused on only a few topics.

Since the virtues of the R&A program (and its current budgetary problems) have already been described in this chapter, COMPLEX comments only briefly here on the mix of mission sizes: small (e.g., Discovery), moderate (e.g., Magellan), and large (e.g., Galileo).

NASA is currently embarking on Discovery, a program of low-cost ($150 million) missions with fast schedules (3 years) and limited measurement objectives. It is argued that such a set of missions will be valuable in producing a steady stream of data, encouraging innovative mission designs or instruments, educating graduate students, and addressing important but narrow objectives. Not surprisingly, most opportunities at present seem to lie with Earth-orbiting telescopes or small missions to the terrestrial planets and comets and asteroids. This area is likely to grow in importance as instruments become miniaturized. Excellent planetary science has been, and can be, done by relatively modest robotic probes (e.g., Explorer 35). Such missions need well-defined objectives, creative engineering, new technologies, and clever orbital strategies.

Large and expensive missions—such as Cassini in planetary science, the Earth Observing System in earth sciences, and the Advanced X-ray Astrophysics Facility in astronomy—were normal new starts approved by Congress around 1990. These capable space missions are a natural outgrowth of scientists' wishing to address more and more complex phenomena. Not surprisingly, these missions have become very costly and are unable to be supported.[10] As a result, a movement has developed to encourage small, fast, and inexpensive missions.

The long travel times between Earth and the outer solar system require long-lived components, specialized power systems, and complex, high-powered communications. This implies that, with current technology, any mission sent beyond the asteroid belt must be very capable. In addition, many of the studies that are preferred in this next phase of solar system exploration, and that may be required to address scientific priorities advocated in this report, require concurrent coordinated observations between the different components of a particular planet or a comet (e.g., simultaneous in situ and remote-sensing observations of Titan's atmosphere by Huygens and Cassini, respectively). Thus, COMPLEX believes that many solar system missions, especially those to the outer solar system, cannot be adequately accomplished by reconfiguration of large spacecraft into one or more small spacecraft.[11]

A mix of studies—from support of individual researchers, through construction and maintenance of ground-based telescopes and laboratories, to low-cost missions with limited measurement goals, to large missions—will be necessary to address all the objectives for planetary science.

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6

Priorities and Recommendations

Since the exploration of the solar system by spacecraft started less than 30 years ago, major progress has been made in documenting the properties of the solar system's contents. We have also significantly advanced our understanding of the processes whereby this complex system of planets and satellites, comets and asteroids, and particles and fields operates. Reviewing these advances and posing the key remaining questions, as detailed in Chapters 3 and 4, make it clear that we have, in essence, come full circle. Although our questions are now framed in terms of the scientific sophistication that has accrued in the four centuries since Galileo first trained his crude spyglass on the Moon and planets, we are still striving to answer questions like those that perplexed ancient priests: What are the heavenly bodies, especially the planets? What forces govern Earth's daily operation and determine its ultimate fate? By what means did Earth come into existence? How did life arise on Earth, and do other intelligent beings exist? Today's versions of these questions fall naturally into one of two distinct categories:

1. How did the solar system originate? How have its constituents evolved? To what extent are the origin and evolution of life a consequence of these events? How did life arise on Earth, and are we humans unique?
2. How, in general, do planets work? In particular, what does their operation say about physical and chemical processes on Earth? What governs the geological evolution of planetary surfaces? What insights do planets give us about understanding how the diverse phenomena observed in complex systems all arise from the application of the same basic laws of physics and chemistry?

Until recently, scientists studying our planet confronted a pair of daunting problems: Earth is an exceedingly complicated body; and, worse still, it was unique insofar as it alone could be examined. Researchers who consider living organisms faced similar problems: life, too, is very complex, and its only known expression is that which is found here on our planet. Now with the information being gathered by studies of other planets, we have the initial glimmerings of how to approach the questions of origins, and we have also begun to tackle in a systematic manner the questions posed by planetary processes.

Wherever we have trained our telescopes or directed our robotic surrogates in the solar system and beyond, new knowledge has been discovered that helps address issues in these two broad categories. But a natural question arises: Are some research topics more fertile than others? Alternatively, are studies of some objects more likely than other investigations to yield answers to fundamental questions?

Setting priorities or making choices is, paradoxically, both a fundamental human characteristic and an activity fraught with difficulty. Nowhere, perhaps, is setting priorities more difficult than in scientific research. In something as basic as choosing a mate, humans select among essentially similar objects. However, in prioritizing scientific disciplines, or even techniques within a discipline, we must judge activities with very dissimilar characters and cultures, practices and procedures. How, for example, can the laboratory study of meteorites and telescopic investigations of comets (in which individual researchers still use some equipment that would be recognizable to Jean Baptiste Biot or Edmond Halley) compete in NASA's budget against spacecraft missions to the planets (an activity barely a generation old—involving some of the most technically complex mechanisms ever devised by humans)?

There are myriad worthwhile projects in planetary science capable of being addressed by a variety of techniques, including robotic spacecraft investigations, human in situ exploration, research using ground-based or Earth-orbiting telescopes, and laboratory studies. All can produce illuminating results. Nevertheless, we must make choices. The scientific community does not have the resources, the facilities, or the personnel to undertake all worthy proposals.

In selecting scientific priorities for the planetary sciences as given below, COMPLEX decided that targets for research scrutiny should be chosen according to how well they address the key objectives listed in Chapters 3 and 4. That is, such targets should either enhance our understanding of the origin and evolution of the solar system and life or should clarify the interoperation of the various components (surface, interior, atmosphere, magnetosphere, satellites, and rings) of planetary bodies. High ratings were given to targets that are likely to answer particularly important key questions or those that would provide information relevant to a range of disciplines; targets that seemed especially ripe for progress were also ranked highly. **COMPLEX argues below that, by these criteria, the most useful new programs to emphasize in the period from**

1995 to 2010 are detailed investigations of comets, Mars, and Jupiter and an intensive search for, and characterization of, extrasolar planets. Moreover, priority scientific investigations in each of these areas can be addressed by the full gamut of techniques including small (inexpensive) and large (expensive) robotic probes, ground- and space-based observatories, and laboratory studies and theoretical modeling.

While the setting of priorities has been driven by the outstanding scientific questions outlined in Chapters 3 and 4, the process has naturally also been dependent on a variety of assumptions and practical considerations (outlined in Chapter 2). The assumptions include the anticipated success of missions already in flight (Galileo with its diminished communication capability) and in development (Cassini, Mars Surveyor, Mars Pathfinder, and Near Earth Asteroid Rendezvous). Practical considerations include the relative difficulty of reaching different solar system bodies, operating in orbit, operating on their surfaces, and returning samples to Earth. COMPLEX assumed that the evolution of space technology over the next decade would not dramatically affect the relative costs of orbital, surface, and sample-return missions. Also a factor in the consideration of priorities (especially between comet and asteroid investigations) has been the extent of recent investments in mission planning made by NASA and the science community. Thus the decade of effort spent in planning and developing instruments for a comet rendezvous mission (begun by NASA and then canceled for budgetary reasons) has been a factor.

COMPLEX's priorities represent a strong consensus view that includes all of the above considerations.

BASIC SCIENCE AND INFRASTRUCTURE

Before research priorities in planetary and lunar exploration are summarized, it is appropriate to consider the personnel and the facilities that are necessary for this type of science to be carried out effectively and efficiently. Data, no matter what its precision, resolution, volume, or rate, does not equal understanding. Data analysis and basic research are needed to turn raw bits into new knowledge. NASA's research and analysis (R&A) program has supported an enormous breadth of successful and stimulating intellectual ventures that are carried out across the nation in universities, federal laboratories, nonprofit organizations, and industry. These studies include, for example, ingenious observations designed to elucidate the individual characteristics of distant Pluto and Charon; sophisticated ion-microprobe analyses of minute interstellar grains to disclose events that predate the birth of the solar system; complicated celestial mechanical simulations to learn previous planetary orbital histories half-way back to the beginning of time; the mining of archival data long after spacecraft missions end to reveal the inner turmoil in Jupiter's Great Red Spot; and extensive surveys of the many minor planets to show that these objects cluster into a few classes. The R&A program has produced many surprising findings and fundamental insights.

Support of this program requires a reliable source of funds. These monies are used not only for the salaries of individual scientists and for their assistants and students, but also for hardware development, laboratory equipment, and telescope instrumentation. For many years NASA has built and supported research facilities (e.g., the Infrared Telescope Facility, Kuiper Airborne Observatory, and Lunar Curatorial Facility) that have been, and are, extremely productive for planetary science. In the last few years, NASA has been less willing to devote substantial resources to research infrastructure and, partly for this reason, the United States is no longer the world's undisputed leader in astronomical technology. This trend should be reversed. A healthy research program requires the infusion of some funds, but more important, this support should be provided in a predictable manner. NASA's recent custom of paying for mission cost overruns with research funds has been very damaging to the R&A program.

While the R&A effort has been a rich and remarkably successful intellectual pursuit, it is also vital to NASA's flight program for several reasons. First, describing the solar system's inhabitants, and, especially, unraveling the processes that act on them, are essential to placing in their scientific context the highly publicized results obtained by glamorous space probes. Second, the ability to correctly define a mission's objectives is greatly enhanced by the stream of background information supplied by the ongoing discoveries of individual R&A investigators. Finally, if the nation is seriously committed to continuing its program of solar system exploration into the next millennium, as implied, for example, by the approval of the Cassini mission, the cadre of talented individuals who will guide this program in 2010 must be trained in the next few years. It is essential for the long-term well-being of the program that it attract good new investigators in each review cycle. In a very real sense, the research performed by principal investigators is the heart, soul, and future of our nation's planetary exploration program.

For these reasons, COMPLEX considers a vigorous R&A program as a fundamental prerequisite to a successful U.S. effort in planetary and lunar exploration.

UNDERSTANDING ORIGINS

Where do we come from? The question is as old as mankind. All human civilizations and cultures have had their own creation myths: late-20th-century society is no different. The account of creation devised by contemporary Western culture may be anchored in the quantitative language of science, but it is as much a response to the basic human need to know "what came before me" as are the creation stories of the !Kung or the Assyrians. From a scientific perspective we can make little progress in addressing this issue until we can answer the question, Are planets and life commonplace in the universe or unique to the solar system?

This question can and should be attacked simultaneously from two different directions. First, we should search for planetary systems around other stars and, if any are identified, determine their physical characteristics. Second, we should try to infer the conditions in the very early solar system so as to ascertain the factors that led to the formation of the planets and to the origin of life on at least one of those planets.

The first approach is essentially an exercise in classical observational astronomy requiring the construction and use of appropriate ground- and/or space-based telescopes. The second approach requires the identification and analysis of material that has remained essentially unchanged (or has been modified in a known manner) since the origin of the solar system.

Today both activities are ripe for substantial progress. After a hiatus of a half century, the last decade has witnessed a renaissance in the manufacture of large telescopes. In addition, technology is now available to realize the scientific promise revealed by the crude optical interferometers constructed by Albert A. Michelson and Francis G. Pease early in this century. These techniques, combined with solid-state detectors descended from those born in the microelectronics revolution of the 1970s, open the possibility of constructing ground- and, ultimately, space-based instruments capable of detecting Jupiter- and, perhaps, Earth-size planets around the nearest stars.

Similarly, improved instruments and new analytical techniques are available to be applied to the study of primitive materials. Major advances are expected in the next decade in understanding the nature and provenance of these ancient particles. For example, the tantalizing data returned from interplanetary dust particles collected by high-altitude aircraft; interstellar inclusions found in various meteorites; and preliminary spacecraft encounters with comets Giacobini-Zinner, Halley, and Grigg-Skjellerup illustrate the type and range of information extractable from meteorites and cometary samples.

Fundamental to the origin of life on Earth was the accretion of organic chemicals with sufficient complexity to spark the self-replicating molecules that led to the first cells. Organic materials are known to occur on many objects in the solar system, including planets, their satellites, and primitive bodies, and in objects in interstellar space. Key to understanding the processes resulting in organosynthesis is an inventory of organic compounds associated with extraterrestrial settings.

As described below, COMPLEX believes that a detailed study of cometary materials and an attempt to find and characterize extrasolar planets are the most important areas to address if we are to understand origins.

Comets

COMPLEX argues in Chapter 3 that comets play a crucial role in our understanding of origins. For all other classes of solar system objects, the primordial record is highly contaminated. To obtain the best information on the original composition of comets, it is important to study unaltered materials from beneath cometary surface crusts. Knowing the elemental, isotopic, chemical, and mineralogical makeup of this material (and its variability from comet to comet) will be critical to opening up the mysteries of the solar system's origin. This same material should also provide important information on the biogenic compounds with which the solar system was endowed 4.5 billion years ago.

A prime consideration in future missions—the need to understand how comets work—will be furthered by rendezvous missions that permit prolonged observation of cometary surface processes, knowledge of which is needed to interpret remote observations of comets in terms of the actual physical processes occurring in the nucleus. But to achieve the ultimate objectives identified by COMPLEX, it will almost certainly be necessary to retrieve samples from deep in the nucleus of several comets. If so, we will first need to measure basic physical properties such as mean density, rotation state, and surface characteristics, and to understand in detail the morphology and active surface processes.

While the main thrust of cometary research should be on the composition of the nucleus to understand origins, other branches of the planetary sciences have much to learn from comets. For example, data of substantial interest to magnetospheric physicists puzzling over dusty plasmas will be obtained, as will information about the processes active on small solar system bodies. In addition, atmospheric scientists may learn more about the nature of escaping atmospheres by studying the gases that evaporate from the nucleus and stream out through the cometary coma.

It should be noted that investigations of the sort endorsed here have been supported by the scientific community in the United States and Europe for many years. For instance, the CRAF mission would have accomplished many of the objectives that COMPLEX espouses. The European Space Agency's Rosetta mission may be able to perform some of the relevant studies, and the United States should carefully consider whether its objectives can be satisfied by joining this approved mission. Cometary investigations are not just the domain of large and expensive missions such as CRAF: important priorities (such as the measurement of physical characteristics necessary to enable more ambitious missions) may be addressed in skillfully crafted missions by small spacecraft. Moreover, laboratory measurements of interplanetary dust particles and telescopic observations will continue to play their traditional role as important sources of information about comets.

Search for Other Planetary Systems

It is clear that to truly comprehend the origin of the solar system and to learn whether life as it is known on Earth is unique, it will be necessary to seek planets around stars other than the Sun. Only after a definitive search has been carried out with sophisticated instruments will it be known how to generalize. While the mere detection of an extrasolar planet will arouse great public interest, that discovery alone will not be sufficient for understanding how the solar system originated. To understand planetary accumulation, observers must also be able to determine, for a statistically significant sample, the basic physical parameters of the planets in these newly found systems: mass, orbital elements, and, for considerations of life, atmospheric temperatures and compositions. These latter properties would also provide important information on the environment in which the system formed and would be an enormous stimulus to comparative planetology.

It is important that any program devised to find extrasolar planets should also be capable of sensing the properties of the protoplanetary disks that are now being found to be ubiquitous accessories to young stars. These studies should provide information that constrains otherwise purely theoretical models of planet-forming disks.

This area of research, at the juncture of planetary science and astrophysics, is already an emerging discipline ripe for attack using a multiplicity of approaches, including optical imaging and infrared and radio interferometry. Today, fresh data, sophisticated simulations, and new theoretical insights are synergistically interacting to rapidly advance understanding. Nevertheless path-breaking instruments will be required to reach the accuracies required for meaningful constraints to be placed on our models of planet formation.

UNDERSTANDING PLANETS

As an area of science progresses, the study of its subjects moves from observation to categorization, then to hypothesis, and finally to comprehension. For planetary science, the first stages of observation and categorization are drawing to a close. Except for distant Pluto and Charon, every planet in the solar system and most major satellites have been visited by at least one flyby mission; both Mars and Venus have been scrutinized by landers and, for extended periods, by orbiting spacecraft. Starting in late 1995, Jupiter will be studied by the Galileo orbiter and atmospheric probe, while a decade later the saturnian system will be examined by the Cassini orbiter and Huygens probe, currently under development.

Now that the reconnaissance phase of solar system exploration is ending, how do we begin to understand planets? The first step is to recognize the different physical systems (atmosphere, interior, surface, magnetosphere, and rings) that make up a planet, as discussed in Chapter 4. We must then compare how the systems work for the various planets. At the same time, because these systems are mutually interacting to a great degree, they, too, must be investigated for the separate planets.

An atmosphere, for example, does not originate and evolve in isolation from the other parts of a planet. After accumulating during the planet's birth or later being outgassed from its interior, the atmosphere will interact to a considerable degree with surface layers (for solid planets) or communicate with the deep interior (for gas giants). Similarly, throughout a planet's history the atmosphere may supply most of the magnetosphere's constituents. More fundamentally, atmospheric chemistry may be intimately involved in processes related to origins and the formation of biogenic compounds.

The mutual interaction of physical systems is evident also in the character of a planet's magnetosphere, which is tied closely to the planet's interior structure and to the ions that it receives from the contiguous atmosphere or from embedded satellites and rings; in turn the magnetosphere alters these constituents. Because the various parts of planets interact in complicated ways, it is valuable to study planets as whole entities.

In this new phase of planetary exploration, which involves seeking understanding rather than simply making maps, is it better to study a few individual planets in great detail or to examine an interesting area of research across the solar system? There is no definitive answer. Certain topics are likely to yield insights if they are studied by a series of missions with limited objectives, amenable to the use of small, relatively inexpensive spacecraft. Others will require comprehensive programs that observe several aspects of a planet at once, thus necessitating, perhaps, intermediate or large missions. But it is unrealistic to imagine that all planets can be studied in depth or even that the intensive study necessary to understand some interacting components of all the planets can be planned, let alone begun, in the time frame of this strategy. A more appropriate manner in which to begin this second phase of solar system study, one that does not strain the bounds of financial and technical possibilities, is to focus on key objects that are representative of their class and are addressable by a variety of techniques.

This approach—to emphasize particular targets because they capture many aspects of planetary behavior or epitomize certain processes—of course meshes well with the engineering reality that spacecraft usually can stop easily only at one place. The key questions and the critical objectives that follow the summaries of scientific themes in Chapter 4 indicate clearly that Mars and Jupiter are the preferred sites to study to gain an understanding of how planets work. While it is surely true that one of these is a terrestrial planet and the other a gas giant, it should be stressed that in its choice of priorities COMPLEX did not set out to select one from each category. Rather, these objects were emphasized because of their particular merits.

Mars

As described in Chapter 4, except for Earth, Mars is the richest of the terrestrial planets in terms of the phenomena it displays. For this reason, synergistic studies of Mars and Earth may help unlock the secrets of both globes. Mars is also a planet that fascinates the public, owing to its potential as a target for human exploration and to the possibility of its being an abode of past life. From a spacecraft engineering standpoint, the Red Planet is also one of the easiest objects to explore because of its proximity to Earth, its modest size, and its thin atmosphere. Nevertheless, the numerous failures of martian missions, most recently Mars Observer, testify to the technical challenge of all long-duration flights.

Had it succeeded, Mars Observer would have surveyed the global elemental geochemical and physical characteristics of the martian surface, monitored atmospheric structure and circulation for 1 full Mars-year, indirectly constrained the planet's interior structure by means of topography and gravity data, established the distribution of volatiles, and clarified the nature of Mars's magnetic environment. As Chapter 4 indicates, these measurements remain of high scientific value, and COMPLEX endorses a prompt reflight of a highly capable orbiter mission or series of orbiters.

Mars is a marvelous place to study the processes that control atmospheric dynamics on terrestrial planets. Significant progress can be made through the deployment of a long-lived global network of surface meteorological stations. These outposts should provide essential data on the daily weather and, when combined with simultaneous sounding from orbit, will lead to much-improved general circulation models. These stations should also be used to determine the seasonal cycles of carbon dioxide, water, and dust and thereby learn something about how the layered martian polar sediments are deposited. In situ measurements of these deposits may allow dating of the polar laminae, in which case a chronology of martian climate change can be established. More accurate determination of rare-gas and isotopic abundances, plus estimates of water trapped in the martian crust, may usefully constrain Mars's ancient climate. Other abundant and dramatic evidence for climate change should be scrutinized and dated. This may stimulate a major improvement in understanding the vagaries of Earth's climate.

One of the outstanding unknowns in geophysics concerns the internal structures of planets. This subject has profound ramifications for studies of origins and surface geology, since differentiation provides heat to mix the original materials and to shape later events. The easiest way to probe beneath Mars's surface is with a set of widely spaced seismometers that could be placed aboard the meteorological stations described above. These same stations should carry sophisticated geochemical laboratories to assay local materials.

The primary reason for again visiting the next planet out from Earth is to compare its processes to terrestrial ones. Nonetheless, by yielding data concerning its early chemical evolution, Mars may also be a linchpin in learning about how life originated on Earth. Although it is unlikely that Mars harbors living organisms today, it is possible that prebiotic organic compounds accumulated on the early Mars and that traces remain today. The prospect of searching for evidence of past life or the chemical evolutionary steps leading to life is a significant motivation for the study of the martian surface. Finally, Mars is one of the two planets whose solar wind interaction has not yet been surveyed.

In addition to its scientific significance, Mars is important for another reason. As already mentioned, it is the most probable target for human exploration beyond the Moon. The Space Studies Board's Committee on Human Exploration (CHEX) stressed in its first report that even though human exploration is not motivated by scientific considerations and is not necessary to achieve any particular scientific priorities, the research community has the opportunity and obligation to provide the best and most constructive scientific advice it can to help the nation accomplish its space goals.[1] This view reflects the conclusions in an earlier report on space policy prepared by the National Academy of Sciences and the National Academy of Engineering.[2] The second CHEX report commented that "an orderly series of future robotic missions will be required for collection of data relevant to human safety, for site selection, and for the effective identification and development of enabled scientific opportunities. Such a series of robotic missions would include many that would be a normal complement of an ongoing robotic planetary science program."[3]

Jupiter

Perhaps appropriately for its size, the largest of the planets displays a dazzling array of phenomena, especially for the study of atmospheric dynamics and magnetospheric physics. In terms of mission planning, Jupiter is also favored as the most accessible of the giant planets. Accordingly, Jupiter is a most worthy target for extended study. This will remain true even following the investigations of the Galileo mission scheduled for the mid-1990s. Not only will that ill-fated spacecraft not perform as well as originally planned, but even the baseline mission would not have been able to accomplish all the high-priority objectives in this system. For reasons of safety and limited energy resources, Galileo's orbit is not ideal for all magnetospheric studies since the fierce (and lethal) inner magnetosphere will not be penetrated, and its complement of instruments, selected nearly 20 years ago, is not completely satisfactory for atmospheric studies. High-latitude regions, which are valuable for viewing polar atmospheric motions and auroral emissions, were not well surveyed by Voyager and will not be by Galileo.

Jupiter is clearly the planet at which to study the most important problem for atmospheric dynamics, namely, the relative influence of solar energy compared to that of internal heat carried upward by convection in driving large-scale motions. The unexplored polar regions should also be observed so that the planet's global circulation can be fully characterized. It is possible that refined isotopic measurements at Jupiter will help clarify aspects of the origin of the solar system.

No other magnetosphere in the solar system can rival Jupiter's in terms of energy, plasma production, and complexity. It is the prototypical rotationally driven magnetosphere. The region inward of Europa's orbit is especially active. The Io-magnetosphere interaction is an excellent example of plasma/neutral gas phenomena. Species from Io populate the magnetosphere with heavy ions. The innermost Galilean satellite also plays a critical part in driving the very intense jovian aurorae.

In the jovian system, the Galilean satellites exhibit many features worthy of study. The Galileo mission should make significant advances in this area, but Io, which is slated to receive close-up scrutiny just once from the spacecraft, may warrant additional attention. This bizarre satellite forms a unique geophysical object because of its energetic volcanoes and its unusual surface. The odd atmosphere of Io, localized over volcanoes and not quite escaping, is of considerable interest. Here it would be valuable to obtain vertical profiles of the fundamental quantities of composition, density, pressure, and temperature.

Given the importance of the jovian system, the post-Galileo investigations of Jupiter may best be performed by a combination of approaches. Telescopic studies from Earth (given expected developments in adaptive optics) and space-based observatories may be sufficient to perform the synoptic observations of Jupiter's atmosphere necessary to provide the context to interpret data from infrequent spacecraft encounters. Jupiter's polar regions, badly foreshortened in observations from Earth or Galileo, may be studied using a small polar-orbiting satellite. Questions about the deep atmosphere may be addressed by a series of atmospheric probes that can also measure key chemical tracers of vertical mixing. The utility of small orbiters and probes may be greatly enhanced if they are operated in conjunction with a jovian communications relay satellite.

CONCLUDING REMARKS

As is appropriate for a Space Studies Board scientific strategy, the priorities and recommendations contained in this report are based on the expected science yield for a level of effort at which research needs to be done to sustain a vigorous field.[4] Activity below this level would, over the time frame of the strategy, raise questions as to whether the sponsoring agency is fostering genuine progress in the planetary sciences. Nevertheless, the introductory chapters of this report discuss the many different motivations that drive the U.S. program in planetary and lunar exploration. Valid arguments could be made by public officials for giving more or less weight to any of these motivations. In this way, a quite different suite of highlighted research topics might emerge and still be a justifiable expenditure of the national treasury. Even under such circumstances, however, COMPLEX maintains that the final choice should be made with heavy weight assigned to answering the key science questions, as listed in Chapters 3 and 4, as well as the objects highlighted in this final chapter.

The priority listing given in this final chapter has identified just a few targets for future emphasis—comets, Mars, Jupiter, and the search for other planetary systems—as those that COMPLEX in mid-1994 believes to have the highest priority for further study. Emphasizing the second and third would contribute much to understanding how planets function: emphasizing the other two would advance very significantly our appreciation of how the solar system originated. Of the four target areas mentioned, COMPLEX considers that the study of the composition, the physical nature, and processes active on a cometary nucleus is the first among equals because such an investigation, when combined with theory and remote observations of comets, would lead to a major advance in our understanding of the origins of our solar system. This opportunity has not yet received the detailed attention it requires. It should be self-evident that the emphasis on these four research areas could change at some later time, depending on the scientific results returned (or not returned) by the ongoing (Galileo) and approved (Cassini) space missions, as well as by the labors of laboratory analysts, theoreticians, and ground-based observers.

Readers should not be misled by this relatively brief list. Because planetary science is an extraordinarily rich scientific discipline with a recent history, many other opportunities for first-rate research are available from Mercury to Alpha Centauri. As documented in the separate disciplinary sections of Chapters 3 and 4, strong scientific arguments can be made that would conclude that Pluto, Neptune, and the Moon are very important objects to study.

Whichever set of subjects is chosen to be studied by space missions, it is clear that the pursuit of these, and the full interpretation of returned results, will require a healthy intellectual community using first-rate facilities. It is also likely that a variety of approaches—ranging from support of individual researchers, through ground-based telescopes and small probes, to large and expensive missions—will be necessary to address all the objectives for planetary science.

A final comment is in order. It is valuable for a scientific community to reassess occasionally what it has accomplished and what achievements may lie ahead with appropriate planning. That is to say, the process that COMPLEX has undertaken is an important one. However, it is just as important that, once consensus is reached and a direction chosen, a steady hand be on the tiller. The wind may buffet our craft, and continual readjustments may need to be made. But once the course has been charted, the most essential thing is to get on with the voyage.

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